















# NAVAL POSTGRADUATE SCHOOL

## Monterey, California



# THESIS

GROUND-UP-TO-SPACE (GUTS)  
LASER PROPAGATION CODE  
DESCRIPTION AND MANUAL

by

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June 1984

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Approved for public release; distribution unlimited

Prepared for: Dr. Fred Raymond, Code 9110

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Laser Propagation Code  
Description and Manual

by

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## ABSTRACT

GUTSAVG is a high energy laser propagation computer program for ground-to-space applications. Written by Dr. C. E. Hogge from the Air Force Weapons Laboratory, Kirtland AFB, it is one in a family of propagation codes addressing this application. Specifically, GUTSAVG was designed to compute irradiance at the target given a model atmosphere, laser device parameters, and simple target engagement geometry. The transmitter induced effects of beam quality and jitter are considered as are the linear atmospheric effects of scattering, absorption, and turbulence. A thermal blooming model is also included. Adaptive optics compensation can be applied with consideration given to isoplanatic effects.

## TABLE OF CONTENTS

I.	INTRODUCTION . . . . .	10
II.	PROPAGATION FEATURES . . . . .	12
	A. THE MTF APPROACH . . . . .	12
	B. THERMAL FLICKERING . . . . .	14
	C. SCATTERING AND ABSORPTION . . . . .	18
	D. BEAM QUALITY . . . . .	19
	E. TURBULENCE . . . . .	20
	F. JITTER . . . . .	22
	G. ADAPTIVE OPTICS . . . . .	23
III.	PROGRAM AND SUBPROGRAM DESCRIPTION . . . . .	37
	A. PROGRAM INPUTS . . . . .	37
	B. ENGAGEMENT GEOMETRY . . . . .	43
	C. MAIN PROGRAM FLOW DIAGRAM . . . . .	49
	D. SUBROUTINE DESCRIPTION . . . . .	62
	1. AESORE and SCAT . . . . .	62
	2. ALFS and ALFA . . . . .	63
	3. UOCST . . . . .	64
	4. FIELD . . . . .	66
	5. FARFLD . . . . .	67
	6. BCIREI . . . . .	69
	7. DETWAV . . . . .	70
	8. MTFBQ and BM . . . . .	71
	9. ISOTRE . . . . .	73
	10. SCINT and SINTIS . . . . .	73
	11. CN2H . . . . .	75
	12. RHOTRE . . . . .	75
	13. JIT and MTFJIT . . . . .	76



14. PETPHS . . . . .	77
15. RESPHS and CCEFFS . . . . .	78
16. PHVAR . . . . .	80
17. AV . . . . .	80
18. BLOOM . . . . .	81
19. MIFATM . . . . .	83
20. TRBREI . . . . .	84
21. FNRHRC . . . . .	84
22. TITISC . . . . .	85
23. RELTOT . . . . .	85
24. ISOPLA . . . . .	87
25. JC . . . . .	88
APPENDIX A: GUTSAVG INPUT FILE . . . . .	89
APPENDIX E: GUTSAVG CUTPUT FILE . . . . .	90
APPENDIX C: GUTSAVG PROGRAM LISTING . . . . .	94
LIST OF REFERENCES . . . . .	138
INITIAL DISTRIBUTION LIST . . . . .	141

## LIST OF TABLES

I.	AESCIB and SCAT Program Variable Definitions . . .	63
II.	AIFS and ALFA Program Variables and Definitions . . . . .	64
III.	UCCST Program Variables and Definitions . . . . .	66
IV.	FIELD Program Variable Definitions . . . . .	67
V.	FARFID Program Variables and Definitions . . . . .	69
VI.	EQIBEL Program Variables and Definitions . . . . .	70
VII.	DETWAV Program Variables and Definitions . . . . .	71
VIII.	MTFEC and BM Program Variables and Definitions . .	72
IX.	ISCTFB Program Variables and Definitions . . . . .	73
X.	SCINTLS and SCINT Program variables and Definitions . . . . .	75
XI.	RECTFB Program Variables and Definitions . . . . .	76
XII.	JIT and MTFJIT Program Variables and Definitions . . . . .	77
XIII.	FRTFES Program Variables and Definitions . . . . .	78
XIV.	FEVAR, RESPHS, and CCEFS Program Variable Definitions . . . . .	80
XV.	AV Program Variables and Definitions . . . . .	81
XVI.	BICCM Program Variables and Definitions . . . . .	83
XVII.	MTFATM Program Variables and Definitions . . . . .	84
XVIII.	TREBEL and FNIREO Program Variables and Definitions . . . . .	85
XIX.	RELICT Program Variables and Definitions . . . . .	86

## LIST OF FIGURES

2.1	GUTSAVG Thermal Blooming Algorithm . . . . .	25
2.2	Thermal Blooming Algorithm (cont) . . . . .	26
2.3	GUTSAVG Scattering and Absorption Algorithm . . . . .	27
2.4	GUTSAVG Beam Quality Algorithm . . . . .	28
2.5	GUTSAVG Turbulence Algorithm . . . . .	29
2.6	GUTSAVG Jitter Algorithm . . . . .	30
2.7	GUTSAVG Adaptive Optics Algorithm . . . . .	31
2.8	GUTSAVG Adaptive Optics Algorithm (cont) . . . . .	32
2.9	GUTSAVG Adaptive Optics Algorithm (cont) . . . . .	33
2.10	GUTSAVG Adaptive Optics Algorithm (cont) . . . . .	34
2.11	GUTSAVG Adaptive Optics Algorithm (cont) . . . . .	35
2.12	GUTSAVG Adaptive Optics Algorithm (cont) . . . . .	36
3.1	General Engagement Geometry . . . . .	45
3.2	Earth Center Angle (ECANG) . . . . .	46
3.3	Angle Intervals for Irradiance Evaluation . . . . .	47
3.4	Coordinate Translation due to Flight Path Offset . . . . .	48
3.5	Velocity and Position Relative to Transmitter . . . . .	49
3.6	Main Program Flow Diagram . . . . .	51
3.7	Main Program Flow Diagram (cont) . . . . .	52
3.8	Main Program Flow Diagram (cont) . . . . .	53
3.9	Main Program Flow Diagram (cont) . . . . .	54
3.10	Main Program Flow Diagram (cont) . . . . .	55
3.11	Main Program Flow Diagram (cont) . . . . .	56
3.12	Main Program Flow Diagram (cont) . . . . .	57
3.13	Main Program Flow Diagram (cont) . . . . .	58
3.14	Main Program Flow Diagram (cont) . . . . .	59

3.15	Main Program Flow Diagram (cont) . . . . .	60
3.16	Main Program Flow Diagram (cont) . . . . .	61

## I. INTRODUCTION

GUTSAVG is a simplified laser propagation program. It is intended specifically for near vertical ground-to-space applications utilizing a fixed earth-based transmitter directed at a single target satellite. The primary purpose of the program is to provide irradiance and fluence on target along with related propagation data.

The program was written by Charles B. Hogge from the Air Force Weapons Laboratory, Kirtland Air Force Base, Albuquerque, New Mexico. GUTSAVG is one of a family of ground-to-space propagation programs. Other versions include GUTSFP (footprint) and GUTSMTF. GUTSFP computes an engagement envelope based on user supplied irradiance threshold levels. The propagation calculation methods are identical to GUTSAVG. GUTSMTF is a full wave-optics program using fast Fourier transforms in the beam propagation computations.

The basic approach used in GUTSAVG is to utilize modulation transfer functions to characterize effects such as beam quality, jitter, turbulence and to apply these effects at the aperture as a single phase screen. The same approach is used in ESP-IV [Ref. 1]. The general modulation transfer function, (MTF), used in this way is described in following sections along with the development of each beam degrading mechanism. A linearized model is used for thermal blooming which is also effectively applied at the aperture as a phase screen. In the case of blooming, however, the phase variance due to blooming is computed, and the Strehl relation is used to determine the relative irradiance reduction. The effect of thermal blooming and the other spreading effects are combined using both FSS and multiplicative methods. Finally, the average of these two methods is used to determine the



total system irradiance reduction from the diffraction  
limited case.

## II. PROPAGATION FEATURES

### A. THE MTF APPROACH

GUTSAVG uses MTFs to apply and then to consolidate the effects of jitter, beam quality, and turbulence. Essentially, these effects are replaced by a phase screen at the aperture which multiplies the initial complex aperture distribution by a random phase distortion factor.

Lutchenirski and Yura [Ref. 2] have developed an expression for the average intensity at a point P in the far-field due to perturbations at the aperture. The intensity at P is

$$\begin{aligned} I(\bar{\rho}) = & \left(\frac{k}{2\pi z}\right)^2 \int M_{\phi}(\bar{\rho}, z) \exp\left[-\left(\frac{ik}{z}\right)\bar{\rho}\bar{\rho}\right] d\bar{\rho}^2 \\ & + \int U(r+\frac{1}{2}\bar{\rho}) U^*(r-\frac{1}{2}\bar{\rho}) \exp\left[-\left(\frac{i \cdot k}{z}\right)r\bar{\rho}\right] d\bar{r}^2 \end{aligned} \quad (2.1)$$

where

$$\bar{\rho} = |r_2 - r_1| \quad (2.2)$$

and

$$r = \frac{r_2 + r_1}{2} \quad (2.3)$$

$\bar{\rho}$  is the vector from the z axis of symmetry in the far-field to the point P.  $U(r)$  is the aperture distribution and  $M_{\phi}(\bar{\rho}, z)$  is the MTF for the disturbance.  $r_1$  and  $r_2$  are two arbitrary points in the aperture where the phase perturbation is measured.  $\bar{\rho}$  is the distance between the points.  $z$ , in the

case considered here, is a constant. If the phase disturbance is a random Gaussian variable with a known correlation function, then the MTF can be expressed as

$$M_{\phi}(\bar{\rho}) = \langle \exp[i(r_1 - r_2)] \rangle \quad (2.4)$$

In terms of the structure function,

$$M_{\phi}(\bar{\rho}) = \exp[(-\frac{1}{2})D_{\phi}(r_1 - r_2)] \quad (2.5)$$

The second integral in equation 2.1 represents the unnormalized aperture MTF. Normalizing this term with the power in the aperture,  $(P_0)$ , to cause the MTF to be unity at the origin results in

$$I(\bar{\rho}) = \left(\frac{k}{2\pi z}\right)^2 P_0 \int M_{\phi}(\bar{\rho}) M_a(\bar{\rho}) e^{-[ik\bar{\rho}\bar{\rho}]} d\bar{\rho} \quad (2.6)$$

Noting the symmetry of the intensity for a given  $\bar{\rho}$  and expressing  $M_{\phi}(\bar{\rho})$  as the combined effects of jitter, beam quality, and turbulence, equation 2.6 can be rewritten as

$$I(\bar{\rho}) = \left(\frac{k}{2\pi z}\right)^2 P_0 \int M_j(\bar{\rho}) M_t(\bar{\rho}) M_b(\bar{\rho}) M_a(\bar{\rho}) J_0\left(\frac{k\bar{\rho}\bar{\rho}}{z}\right) \bar{\rho} d\bar{\rho} \quad (2.7)$$

A Fourier-Bessel transform has been used. Note that the MTFs of jitter ( $M_j$ ), beam quality ( $M_b$ ), and turbulence ( $M_t$ ) have been substituted for  $M_{\phi}$ .

The ESF-IV manual [Ref. 3] contains the development above in more detail. MTFs for the specific effects are described in following sections.

## E. THERMAL BLOOMING

The thermal blooming model in GUTSAVG is based on the following linearized density perturbation equation.

$$\frac{\Delta \rho}{\rho_0} = \frac{\alpha(\ell)}{V_0} \frac{\gamma-1}{\gamma} \frac{1}{p_0} \int_{-\infty}^{x'} I(x', y) dx' \quad (2.8)$$

$$\times \exp \left[ - \int [\alpha(\ell) + \sigma(\ell)] d\ell \right]$$

Here,  $\alpha(\ell)$  is the atmospheric absorption coefficient at a distance  $\ell$  along the beam,  $V_0$  is a constant transverse wind velocity, and  $p_0$  is the ambient pressure. The exponential term represents the total extinction due to scattering and absorption.  $x'$  is a constant of integration. It is assumed that the beam is propagated in the positive  $z$  direction a distance  $\ell$  and that the wind vector is in the positive  $x$  direction. The intensity integral represents the heating of the atmosphere as it transits the beam [Ref. 4]. Some assumptions embodied in the above equation are that  $V_0 \ll c_0$ , the local sonic velocity, so that the process represented occurs at constant pressure, and that the kinetics of absorption and conversion to heat are extremely fast [Ref. 5].

By applying the Gladstone-Dale relation, the density relation can be expressed as a change in the refractive index.

$$\Delta n = (n_0 - 1) \frac{\Delta \rho}{\rho_0} \quad (2.9)$$

Equation 2.8 can be rewritten as

$$\Delta n = (n_0 - 1) \frac{\alpha(\ell)}{V_0} \frac{\gamma - 1}{\gamma} \frac{1}{P_0} \int_{-\infty}^{x'} I(x', y) dx' \quad (2.10)$$

$$\times \exp \left[ - \int [\alpha(\ell) + \sigma(\ell)] d\ell \right]$$

The change in the wavefront phase of a beam due to the refractive index change when the beam is propagated a distance  $\ell$ , is given by

$$\Delta \phi = \frac{2\pi}{\lambda} \int_0^{\ell} \Delta n d\ell \quad (2.11)$$

Substituting equation 2.10 into 2.11 and changing the limits of integration to reflect the ground-to-space propagation path results in

$$\Delta \phi(x, y) = \left[ \frac{2\pi}{\lambda} \frac{n_0 - 1}{P_0} \frac{\gamma - 1}{\gamma} \int_{-\infty}^{x'} I(x', y) dx' \right] \quad (2.12)$$

$$\times \int_{h_t}^{h_{atm}} \frac{\alpha(h) \exp \left[ -\sec \theta \int_{h_t}^h [\alpha(h) + \sigma(h)] dh \right]}{V_0 \cos \xi + \omega h} dh$$

$h_{atm}$  is the extent of the atmosphere, which is about 30 km, and  $h_t$  is the height of the laser transmitter. Also, the wind term has been expanded to include the relative wind velocity due to slewing.  $V_0$  is assumed to be parallel and opposite in direction of that of the target motion.  $\xi$  is the angle of incidence of the wind to the beam so that  $V_0 \cos(\xi)$  represents the transverse wind.  $\omega h$  is the effective wind generated by slewing.  $\omega$  is the angular slew rate.

The first portion of equation 2.12 is independent of path while the second part is not, assuming  $I(x, y)$  does not change along the propagation path. This assumption is valid only for a very small amount of blooming. The approach used



in GUTSAVG is to determine the phase distortion due to thermal blooming by first evaluating the path invariant part of equation 2.12. This is accomplished by constructing a phase screen at the aperture and then removing the best fit tilt, focus curvature, and mean phase. Zernike polynomials are used to model these aberrations. The result is the residual phase due to thermal blooming alone. The variance of the phase is then computed.

The path dependent term is evaluated within the angle interval loop of the program and is applied to the previously computed phase variance during each path iteration. The path iteration process is diagrammed in the engagement geometry section. Also, see Figures 2.1 and 2.2 for a flow diagram of the general treatment of thermal blooming in the program.

Once the total phase variance has been determined, the Strehl relation is used to compute the intensity degradation due to thermal blooming.

$$\frac{I}{I_0} = \exp(-\sigma^2) \quad (2.13)$$

The result of equation 2.13 is a relative intensity (Irel) ratio.  $I_0$  is the ideal on-axis irradiance with no phase distortion. The Strehl relation above is thought to be too severe a model for Irel below 0.3 [Ref. 6]. For that reason, if  $\sigma^2$  is less than 1.2, the Irel will be computed using polynomial curve fits developed from GUTSMIF results. GUTSMIF is a full wave optics code utilizing fast Fourier transforms. For a description of the curve fit method above, see the subroutine BLOOM explanation. [Ref. 7]

Combining the thermal blooming effect with the other effects, such as turbulence and jitter, is accomplished by averaging the results of two different approaches. The first

approach is the RSS (root sum squared) method. This method of combining the Irel due to the effects of thermal blooming with the Irel due to jitter, beam quality, and turbulence is accomplished as follows

$$Irel_{rss} = \left( 1 + \left[ \frac{1}{Irel_{tb}} - 1 \right] + \left[ \frac{1}{Irel_o} - 1 \right] \right)^{-1} \quad (2.14)$$

where  $Irel_{tb}$  is the thermal blooming result and  $Irel_o$  is the result of the other effects. The second approach is a multiplicative approach and is simply

$$Irel_m = Irel_o \times Irel_{tb} \quad (2.15)$$

The two combined Irels obtained by these methods are then averaged to give the total intensity ratio due to all the attenuating or distorting propagation effects.

$$\frac{I}{I_o} = Irel_{tot} = \frac{Irel_m + Irel_{rss}}{2} \quad (2.16)$$

$I_o$  is the ideal diffraction limited on-axis intensity. The bases for the above averaging process is empirical in nature and is an attempt to adjust the results obtained by the RSS method alone. The results produced by RSS were thought to be too optimistic. The multiplicative method, a more pessimistic approach, was therefore included. The ultimate Irels obtained are very close to those obtained by GUTSMIF, the full wave code. [Ref. 8]

There are some limitations to the thermal blooming model used in GUTSAVG in addition to the assumptions already mentioned. First, the wind ( $V_o$ ) is applied as a constant

everywhere in the atmosphere. At higher altitudes, this is not a major consideration due to the higher relative velocity of the beam. At low to medium altitudes this could affect thermal blooming to an extent to warrant the addition of a wind profile as a function of altitude. This could be done with little effort if the data is available. Also, the program assumes a wind parallel and opposite to the direction of the target motion. This precludes the case of slewing with the wind and the creation of null spots. Transient blooming, which violates one of the original assumptions of the equation used, is not considered [Ref. 9]. For very low altitude satellites, the high slew rates generated would result in a supersonic relative wind across the beam. In this case, the constant pressure assumption is invalid [Ref. 10]. Kinetic cooling and molecular breakdown are also not addressed in GUTSAVG.

### C. SCATTERING AND ABSORPTION

GUTSAVG does not contain any type of atmospheric model with respect to scattering and absorption data. Extinction coefficients must be entered by the user in the appropriate subroutines, ALFS and ALFA, or the program can be modified to accept a separate data file. Once inserted into the program, scattering and absorption coefficients are treated without distinction between aerosol and molecular mechanisms. Therefore, the coefficients used must represent the total effect of scattering or absorption.

$$\alpha(h) = \alpha(h)_{\text{mol}} + \alpha(h)_{\text{aer}} \quad (2.17)$$

$$\sigma(h) = \sigma(h)_{\text{mol}} + \sigma(h)_{\text{aer}} \quad (2.18)$$

Transmission due to scattering and absorption are computed indentically and given by

$$T_a = \exp\left(-\sec\theta \int_{h_t}^{h_{\text{atm}}} \alpha(h) dh\right) \quad (2.19)$$

where  $\theta$  is the zenith angle, and the integration limits are the altitude of the transmitter and the vertical extent of the atmosphere. The extent of the atmosphere in the program is defined as 30 km. Figure 2.3 shows the program application of scattering and absorption.

#### C. BEAM QUALITY

GUTSAVG allows the user to describe the beam at the aperture in terms of the electromagnetic field amplitude distribution and total beam quality. The initial amplitude field used by the program is Gaussian in shape with the user specifying a waist diameter. The waist diameter is defined by the  $1/e^2$  point on the distribution. Truncation of this Gaussian field will of course depend on the aperture diameter and the size of the central obscuration. If the waist diameter is made large compared to the aperture, a more uniform distribution results.

Beam quality at the aperture exit may be specified by two different parameters. One of these is the 'times diffraction limited number',  $N$ .  $N$  has been used in a general way to mean an increase in far-field spot size or as a 'power-in-the-bucket' ratio. In GUTAVG,  $N$  is a total beam quality term. The second beam quality parameter is a nondimensional term representing the RMS phase distortion at the laser wavelength at the exit aperture,  $\frac{\delta_{\text{rms}}}{\lambda}$ .

The parameters are related to each other and to the intensity degradation by

$$\frac{I}{I_0} = \frac{1}{N^2} = \exp - \left( \frac{2\pi\delta_{\text{rms}}}{\lambda} \right)^2 \quad (2.20)$$

To apply beam quality to the propagation problem, an MTF array is constructed representing a phase screen at the aperture. The phase is assumed to be a Gaussian random variable with a zero mean value. For the axi-symmetric beam considered in GULAVG, the MTF is [Ref. 11]

$$M_b(\bar{\rho}) = \exp \left( -k^2 \left[ \sigma^2 - C_\phi(\bar{\rho}) \right] \right) \quad (2.21)$$

$C_\phi$  is the autocorrelation function of the phase and is defined as

$$C_\phi(\bar{\rho}) = \sigma^2 \exp \left[ - \left( \frac{\bar{\rho}}{L} \right)^2 \right] \quad (2.22)$$

where  $\sigma^2$  is the phase variance,  $\left( \frac{2\pi\delta_{\text{rms}}}{\lambda} \right)^2$ , and  $L$  is the phase correlation length [Ref. 12]. The beam quality MTF array is combined with the MTF arrays due to other propagation effects to determine the complete system MTF and, hence, the total irradiance degradation. Based on the provided input parameter, Figure 2.4 shows the general treatment of beam quality within the program.

## E. TURBULENCE

GULAVG uses the Eufnagel model [Ref. 13] for  $C_n^2$  as an indicator of the optical effects of turbulence along the propagation path.  $C_n^2$  is the refractive index structure constant and represents the refractive index in the



atmosphere as a function of turbulence induced density fluctuations. The model is an empirically derived vertical profile of  $C_n^2$ .

Fried [Ref. 14] has developed a parameter which is directly related to the behavior of a coherent beam in a turbulent medium. This term is called the effective coherence diameter,  $r_0$ . In the case of a laser transmitter,  $r_0$  represents a physical limit to the transmitter diameter of a near diffraction-limited beam. For a transmitter diameter,  $D$ , larger than  $r_0$ , degradation of the beam by turbulence will occur. If  $D$  is smaller than  $r_0$ , then near diffraction-limited propagation will be achieved. Beam wander or pure tilt occurs for transmitter diameters approximately equal to  $r_0$ . Yura [Ref. 15] has defined a somewhat different but related term that can be thought of as a lateral coherence length,  $\rho_0$ . These two quantities are given by

$$r_0 = \left[ \frac{2.19}{6.88} k^2 \sec \theta \int C_n^2(h) dh \right]^{-3/5} \quad (2.23)$$

and

$$\rho_0 = \left[ 1.45 k^2 \sec \theta \int C_n^2(h) dh \right]^{-3/5} \quad (2.24)$$

so that

$$\rho_0 = \frac{r_0}{2.1} \quad (2.25)$$

where  $k = \frac{2\pi}{\lambda}$ ,  $\theta$  is the zenith angle, and the limits of integration are  $h_{\text{atm}}$ , the vertical extent of the atmosphere, and  $h_t$ , the height of the transmitter.

$\rho_0$  may be specified by the user as a program input or the program may be allowed to compute it based on equation 2.24 . The user may also input  $\rho_0$  indirectly by specifying the 'seeing conditions' , a quantity used by astronomers to describe angular spread of a stellar point source (see input section and Figure 2.5). The program uses  $\rho_0$  to compute the atmospheric MTF.

The MTF of the turbulent atmosphere is determined by developing the structure function of the turbulence. This development is demonstrated by Yura [Ref. 16]. The resulting MTF is given by

$$M_t(\bar{\rho}) = \exp \left[ - \left( \frac{\bar{\rho}}{\rho_0} \right)^{3/5} \right] \quad (2.26)$$

This MTF effectively applies the the effect of turbulence along the propagation path as a phase screen at the aperture.

## F. JITTER

Beam jitter is a user input and is specified by the variance of the angular excursions of the beam. Using the 2-sigma-p definition,

$$2\sigma_p = \sqrt{2(\sigma_x^2 + \sigma_y^2)} \quad (2.27)$$

where  $\sigma_x$  and  $\sigma_y$  are the axial variances of the jittered beam center in the far-field.  $\sigma_x$  and  $\sigma_y$  are random variables with Gaussian distribution and in the symmetric case , as considered by GUTSAVG,  $\sigma_x = \sigma_y$  . The resultant intensity distribution due to jitter will also be a Gaussian distribution with  $(2\sigma_p)$  representing the spot radius defined at the  $1/e^2$  point. In other words, 86.5% of the beam energy will reside within the radius  $2\sigma_p$  . [Ref. 17]

Jitter can be shown to be a wavefront tilt at the aperture. Using this approach, a phase screen at the aperture can be used to characterize the effects of jitter and a jitter MTF developed. That MTF is given by

$$M_j(\bar{\rho}) = \exp\left[\frac{-k^2 \bar{\rho}^2 (2\sigma_p)^2}{8}\right] \quad (2.28)$$

Figure 2.6 is a general flow diagram for the treatment of jitter within the program.

## G. ADAPTIVE OPTICS

The ability to apply adaptive optics corrections to the propagation problem has been included in GUTSAVG. The user has several options with respect to the type and degree of compensation desired. The following general discussion and figure 2.8 provides the needed insight to the effects of selecting the adaptive optics options.

The major compensation mode provided by the program is invoked by selecting full zonal adaptive optics with consideration given to isoplanatic effects. When selected, this model results in the correction of beam degradation due to turbulence. This is accomplished by correcting turbulence induced tilt and then adjusting  $\rho_0$  so as to produce a predetermined level of adaptive optics performance. This predetermined performance is as measured by the Strehl ratio given a residual phase variance determined by the adaptive optics sensor phase. Parameters determining the phase error are the response bandwidth of the adaptive optics system, the number of system actuators, the reflected radiant intensity of the target, and the target-to-sensor transmission. The resultant  $\rho_0$  found in this manner is then used to compute the atmospheric MTF. When this 'corrected' MTF is used to compute the far-field intensity, the result will represent an adaptive optics corrected value.

Without invoking full zonal adaptive optics, the user may apply a tilt-only correction for turbulence. In this case some or all of the tilt due to turbulence may be removed before computing the atmospheric MTF. The degree of tilt compensation is specified by the user.

As mentioned above, isoplanatic effects are included in the adaptive optics calculations. This is also an option, however, and isoplanatic calculations may be inhibited by the user. The effect considered is the limitation of the adaptive optics system given an isoplanatic angle smaller than the target lead angle. Fried [Ref. 18] provides a discussion of isoplanatism and development of the isoplanatic angle.

Although adaptive optics compensation for thermal blooming is not modeled in a strict sense, a thermal blooming correction factor can be applied. This factor is simply a fractional constant that multiplies the thermal blooming phase variance before the Strehl relation is used to compute the intensity degradation.

Refer to the input definitions and the subroutines involved with adaptive optics. In addition, refer to figure 2.7 for more explanation.

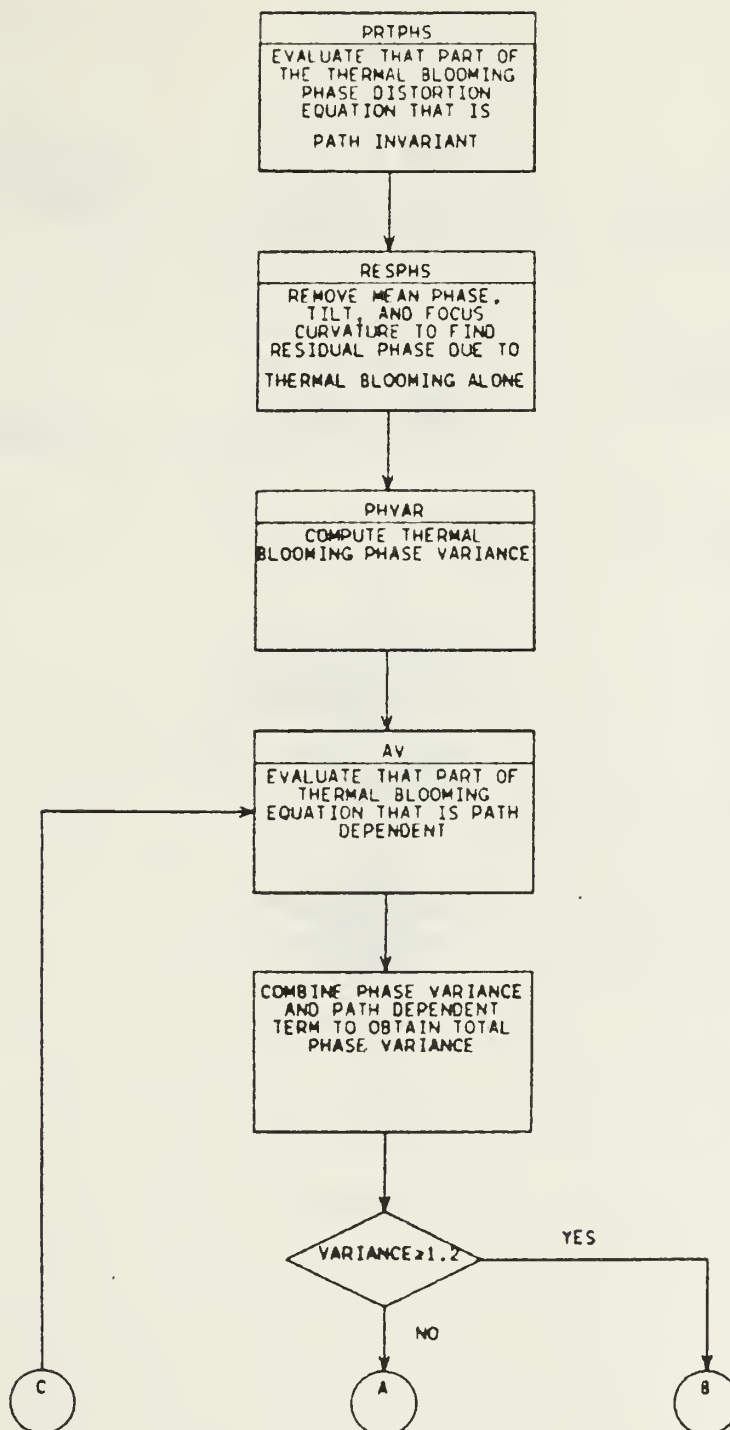


Figure 2.1 GLISAVG Thermal Blooming Algorithm.

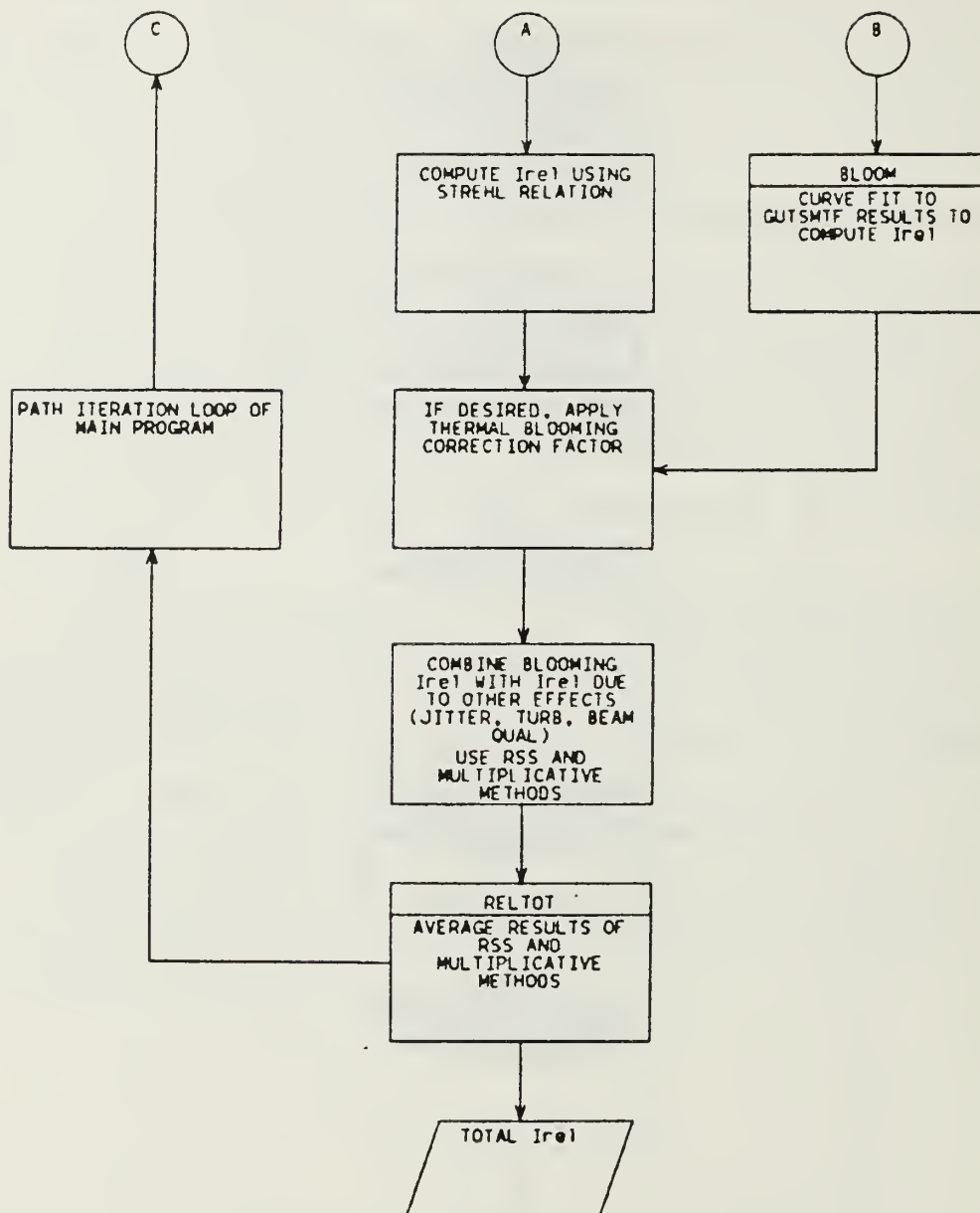


Figure 2.2 Thermal Blooming Algorithm (cont).



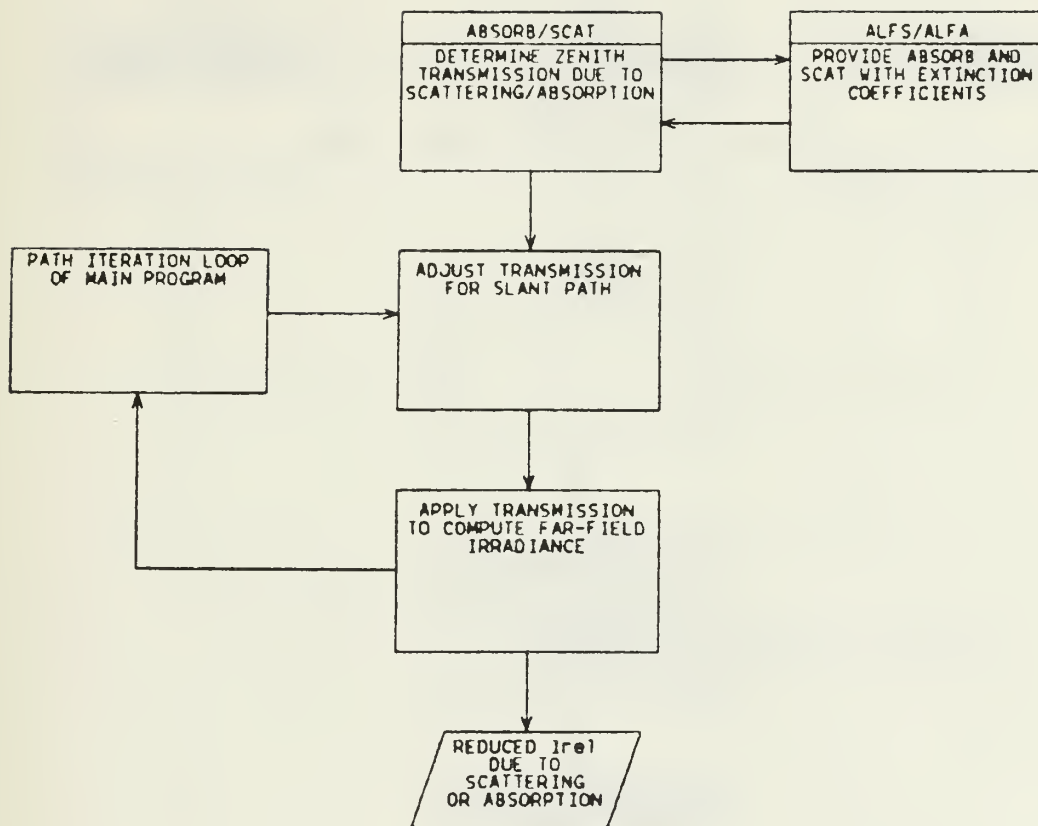


Figure 2.3 GUTSAVG Scattering and Absorption Algorithm.

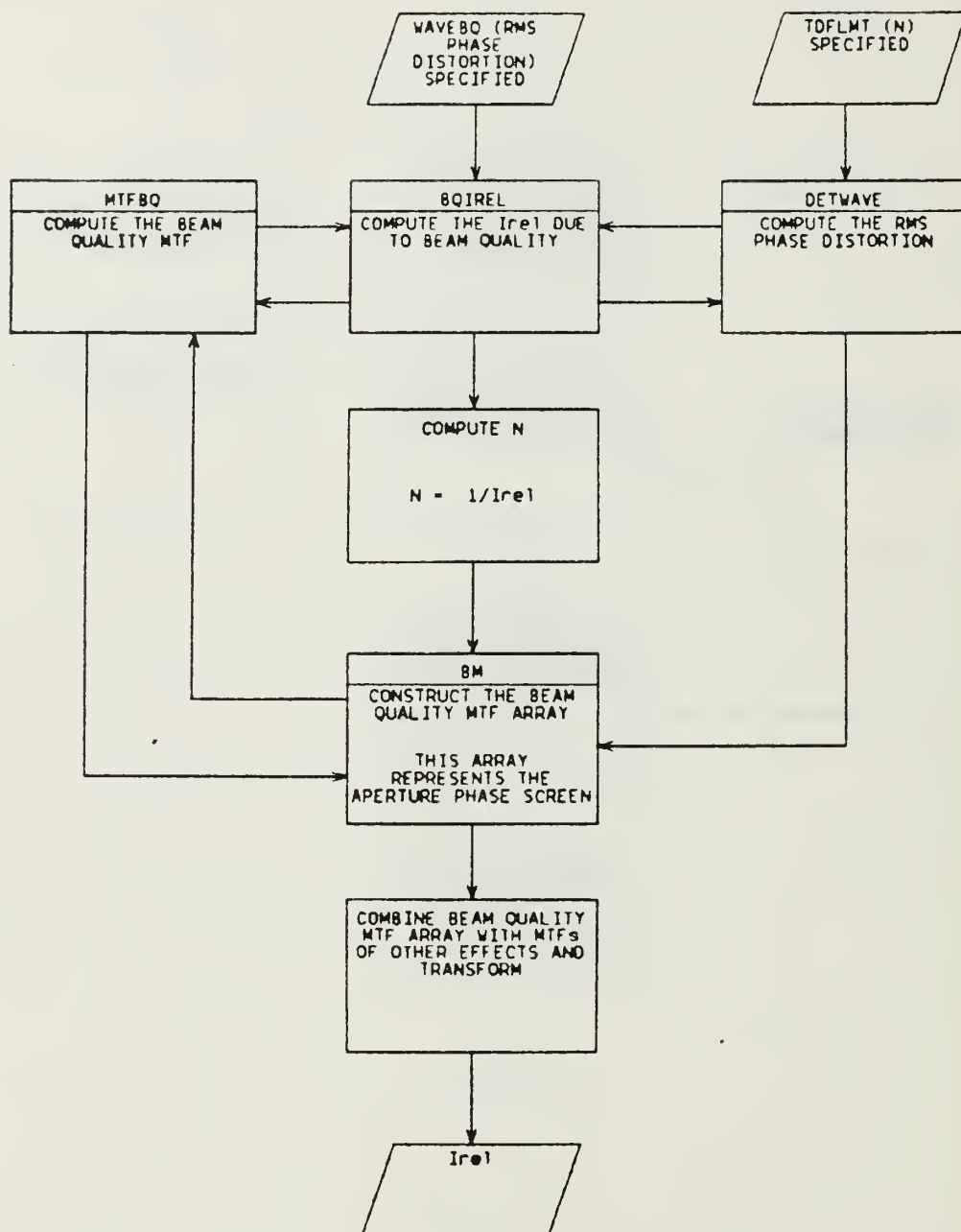


Figure 2.4 GUISAVG Beam Quality Algorithm.

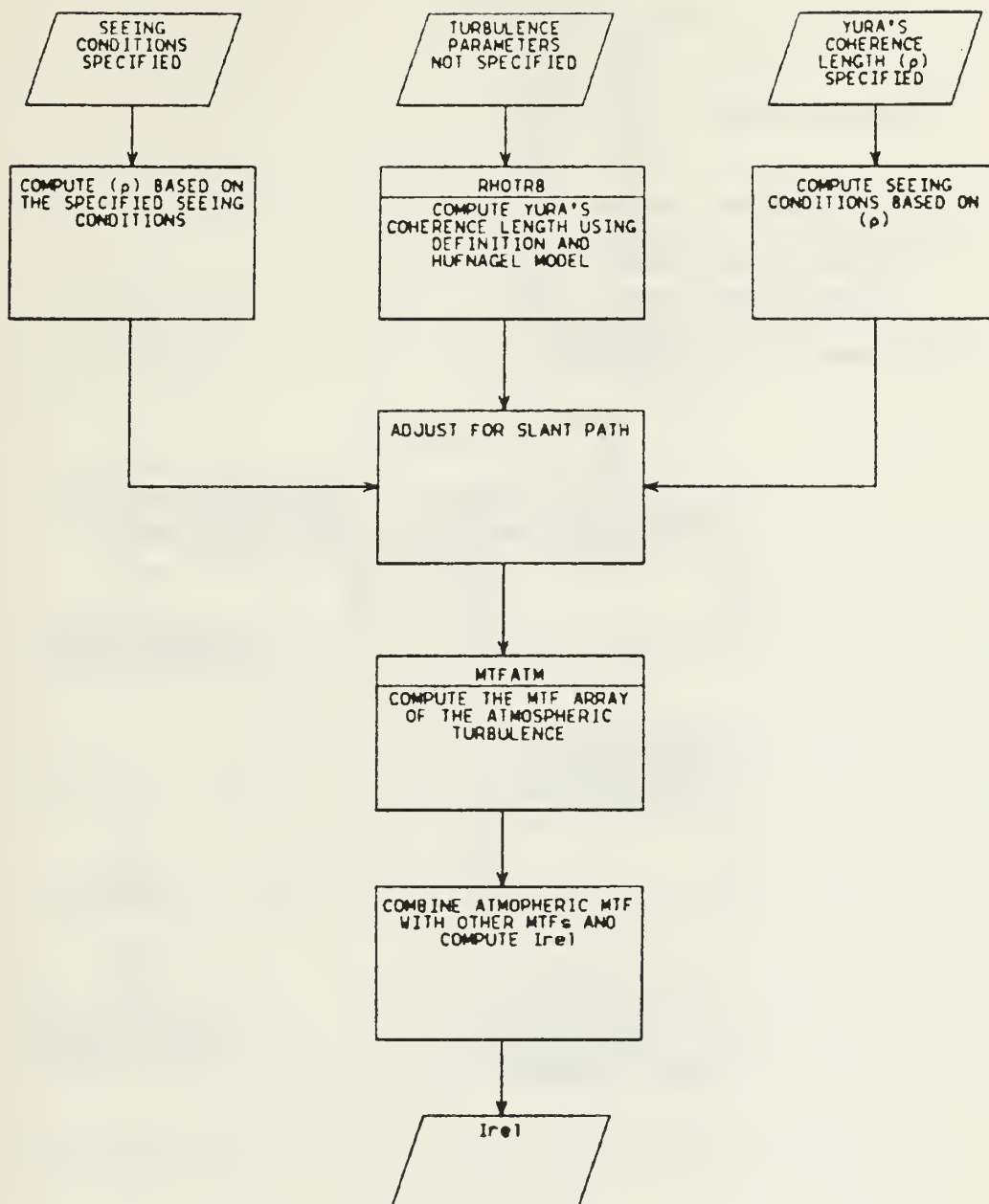


Figure 2.5 GUTSAVG Turbulence Algorithm.

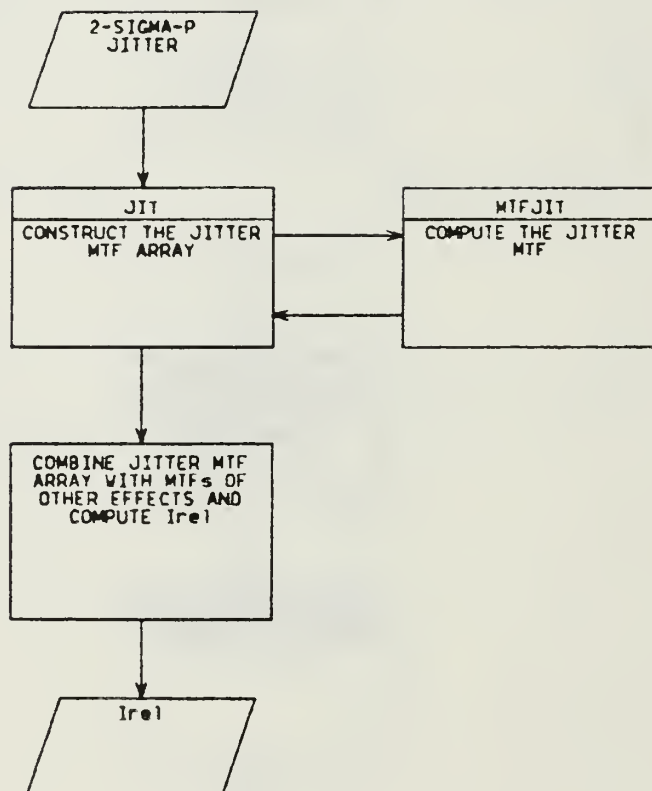


Figure 2.6 GUTSAVG Jitter Algorithm.

# INPUT DECISIONS

NFLAGA	FULL ZONAL AO
1	YES
0	NO
NOISO	INHIBIT ISOPLANATIC CALCULATIONS
1	YES
0	NO
ADAP	RESIDUAL TURBULENCE TILT
0.0	REMOVE 100% OF THE TURBULENCE TILT
1.0	REMOVE 0% OF THE TURBULENCE TILT
AOBLOM	THERMAL BLOOMING CORRECTION
0.0	REMOVE 100% OF THE THERMAL BLOOMING
1.0	REMOVE 0% OF THE THERMAL BLOOMING

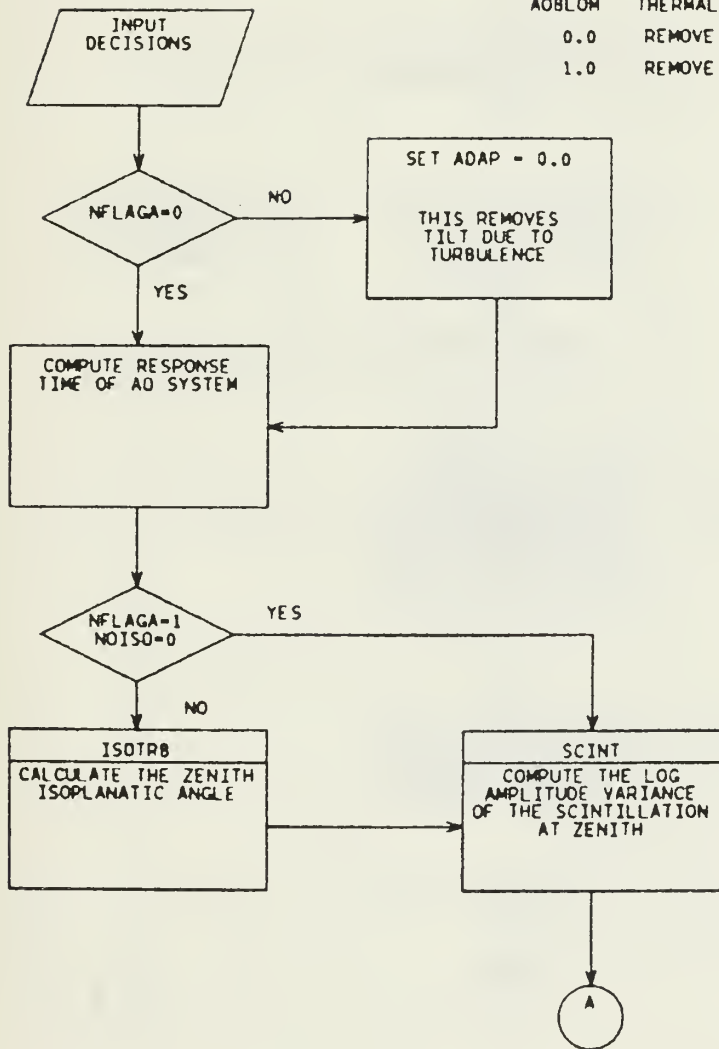


Figure 2.7 GUISAVG Adaptive optics Algorithm.

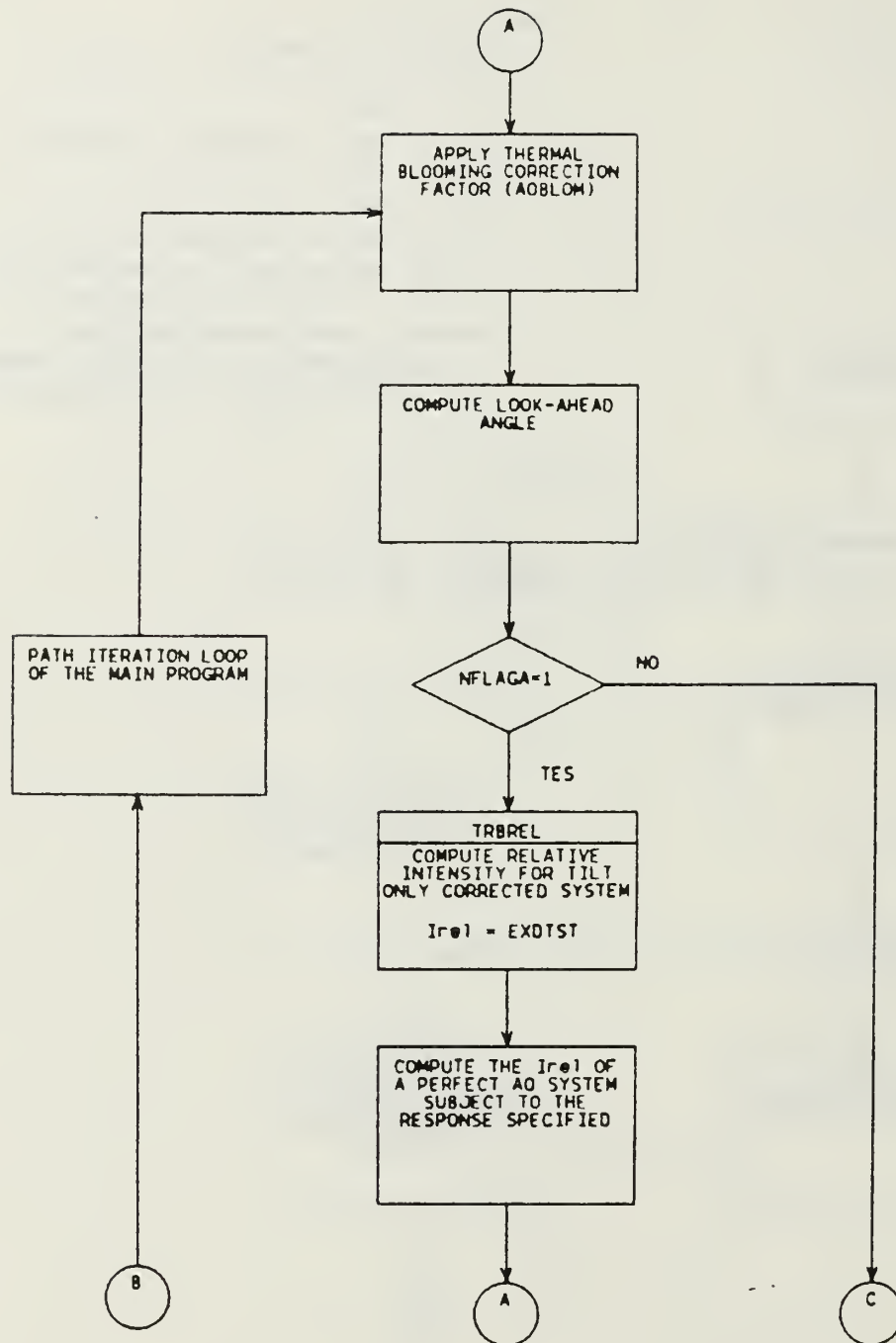


Figure 2.8 GUTSAVG Adaptive Optics Algorithm (cont).



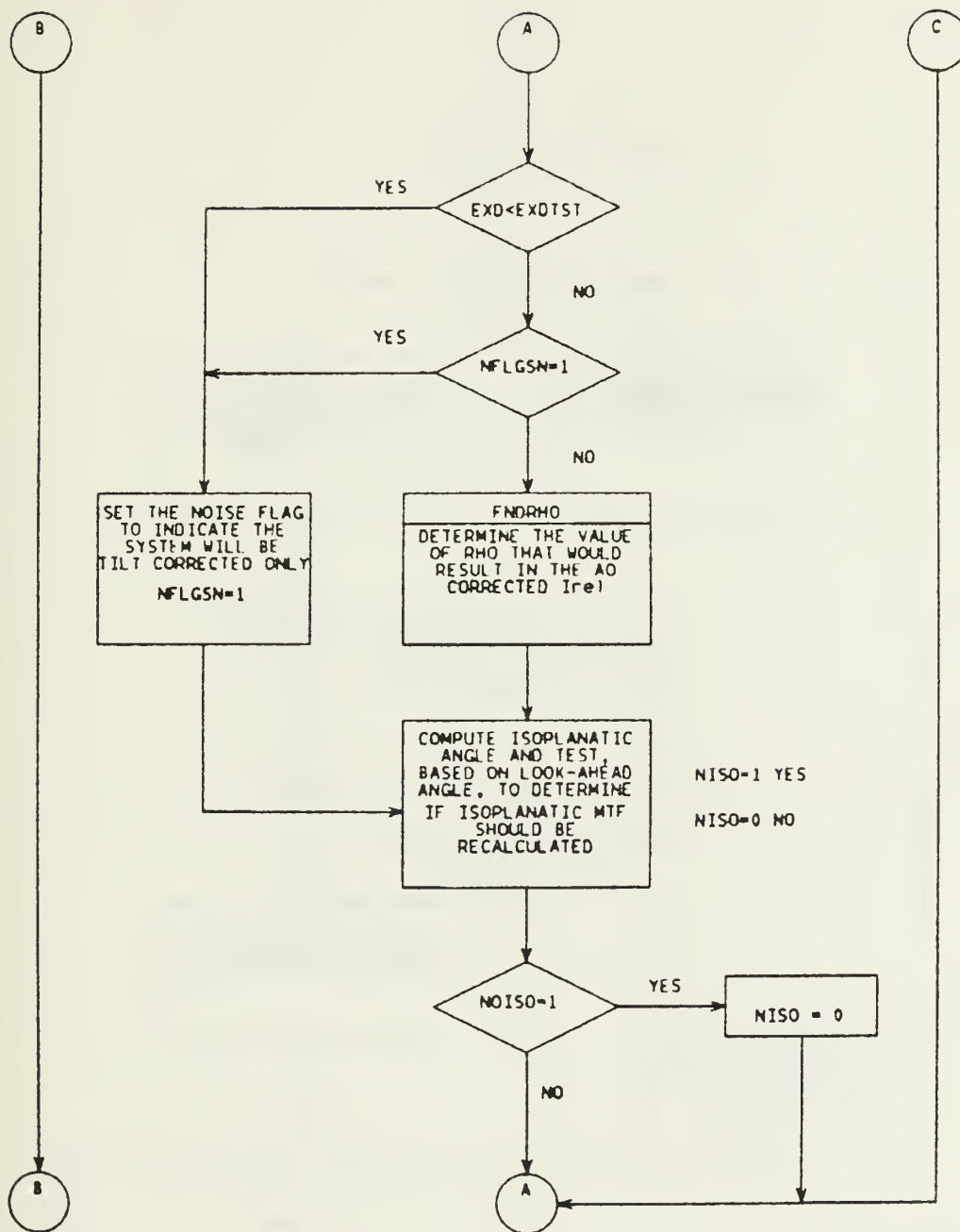


Figure 2.9 GUTSAVG Adaptive Optics Algorithm (ccnt).

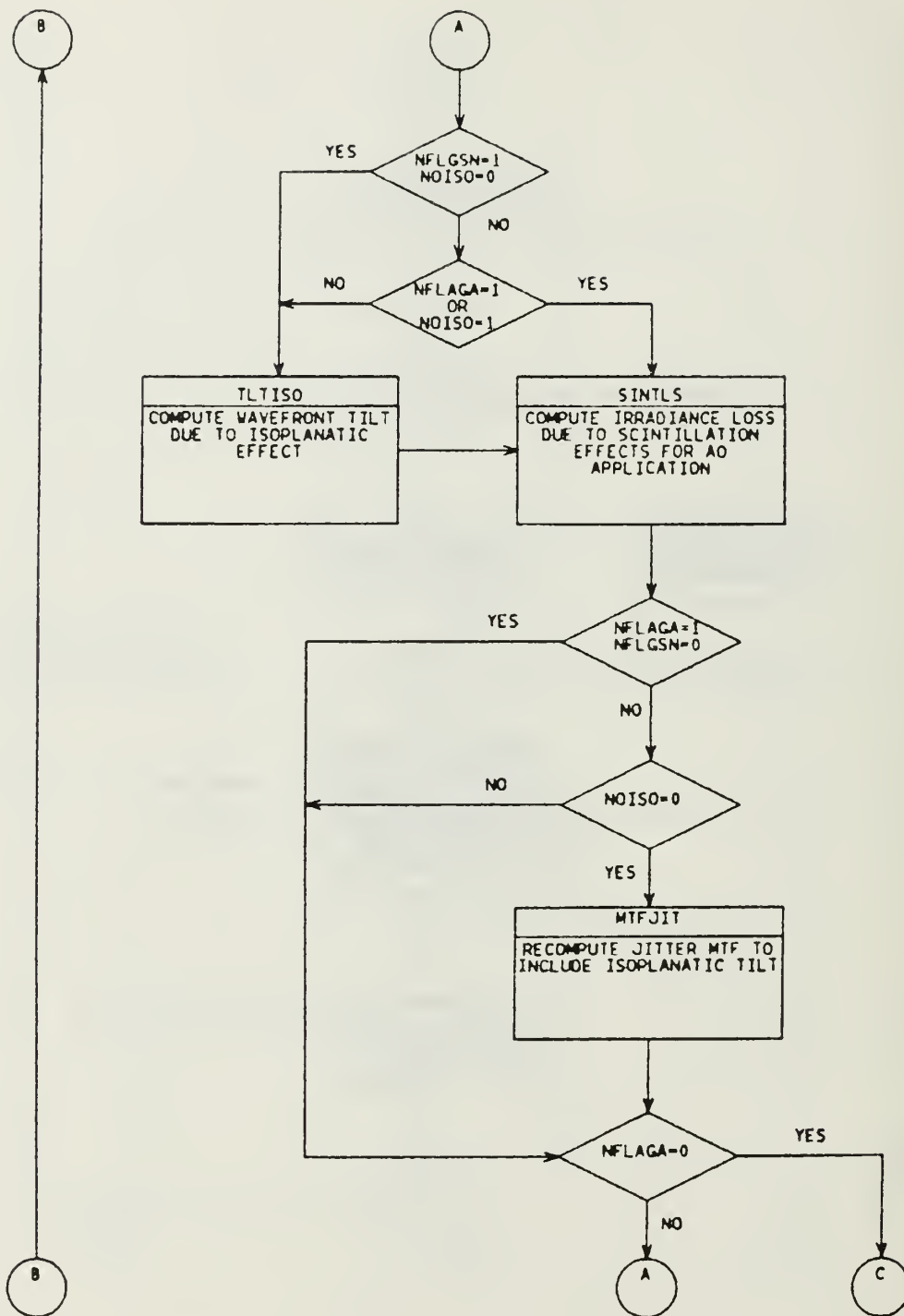


Figure 2.10 GUTSAVG Adaptive Optics Algorithm (cont).

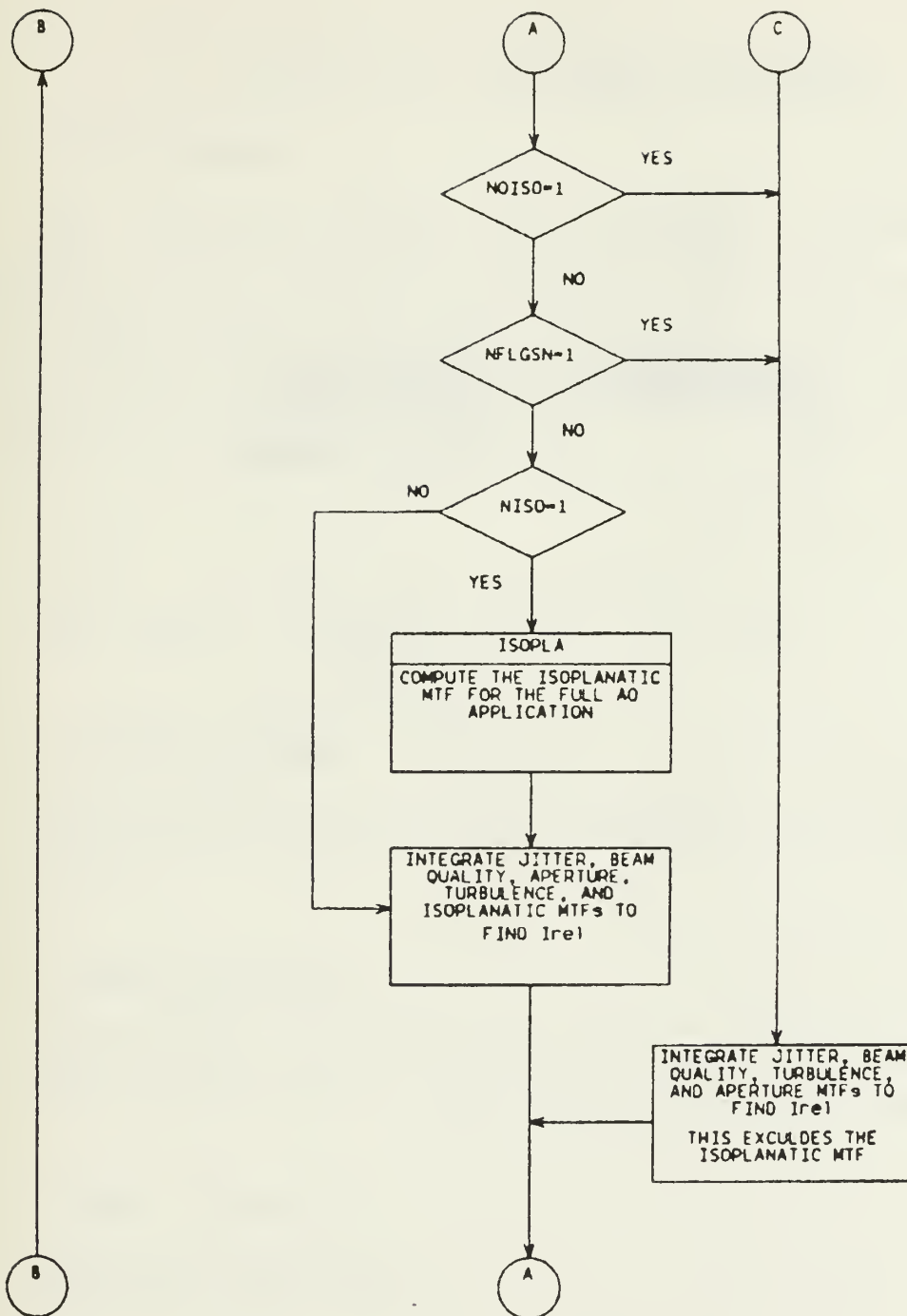


Figure 2.11 GUTSAVG Adaptive Optics Algorithm (ccnt).

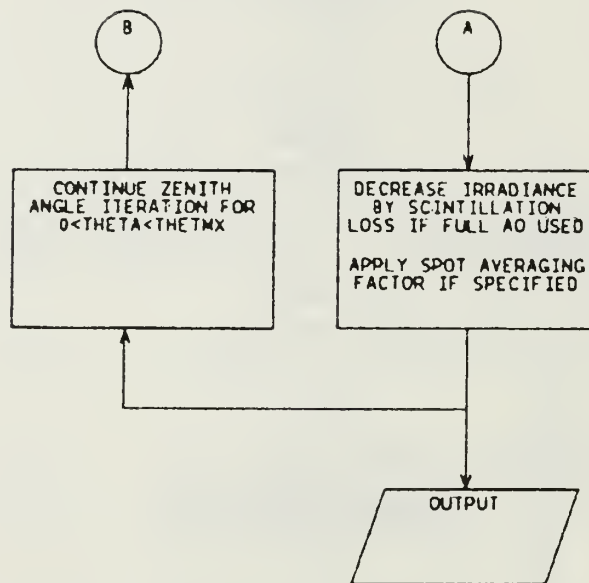


Figure 2.12 GUTSAVG Adaptive Optics Algorithm (ccnt).

### III. PROGRAM AND SUBPROGRAM DESCRIPTION

#### A. PROGRAM INPUTS

The following are the inputs necessary to utilize GUTSAVG. Default values are indicated for parameters not absolutely required for program operation. At NPS these input parameters are entered via an input file. A copy of this file is provided in Appendix A. (\*) indicates a nondimensional parameter.

- DIA (meters)

The diameter of the transmitter aperture.

- DIACES (meters)

The diameter of the central obscuration of the transmitter.

- EFAMS2 (meters)

The Gaussian waist diameter of the amplitude distribution at the aperture. (measured at the  $1/e^2$  point)

- WAVE (meters)

The laser wavelength.

- PTOTAL (Watts)

The total power at the aperture.

• TDFLMT (\*)

This is the often used "times diffraction limited number" and represents total beam quality. As used in GUTS, it is related to the RMS phase distortion at the aperture by the Strehl approximation

$$\frac{1}{(\text{TDFLMT})^2} = \exp \left[ - \left( \frac{2\pi\delta_{\text{rms}}}{\lambda} \right)^2 \right] \quad (3.1)$$

$(\text{TDFLMT})^2$ , therefore, is equivalent to the ratio of the on-axis diffraction limited intensity to the on-axis intensity resulting from the near-field phase distortion,  $\delta_{\text{rms}}$ .

$$\frac{1}{(\text{TDFLMT})^2} = \frac{I}{I_0} \quad (3.2)$$

For a discussion of the limitation of 3.1, see [Ref. 19].

• WAVEBQ (\*)

This term is the RMS phase distortion at the laser aperture, nondimensionalized by the wavelength.

$$\text{WAVEBQ} = \frac{\delta_{\text{rms}}}{\lambda} \quad (3.3)$$

• SCALEQ (meters)      default = DIA/5

This term is the transverse phase correlation length at the aperture.



- THSEE (arcsec)      default = f(RH00)

This is a qualitative term used by astronomers to describe 'seeing conditions' in the visible range. If a point source is viewed from the earth, it may not appear as a point source but as a 'smear' or spot. The angular spread of this spot is the parameter THSEE. If RH00 is not specified as an input and THSEE is, the program will use THSEE to compute RH00. Other than this case, THSEE is not used but will be computed as a function of RH00 and included as an output.

- HGRND (meters)

The height of the ground at the transmitter position above MSL.

- HTRANS (meters)

The height of the transmitter above.

- HSAT (meters)

The orbital altitude of the satellite above MSL (at zenith).

- THETMX (degrees)

THETMX is the angle measured from zenith below which the laser will not transmit for a zenith pass. For offset flight paths, it should be noted that the transmitter will point below this value. For an illustration of the engagement envelope, see figure 3.1

- ICFF (meters)

For a target that does not pass direct overhead, this input specifies the amount that the target ground track is offset from the ground track of the overhead case. It is the distance, as measured from the transmitter, to a perpendicular intersection on the ground track.

- RHCO (meters) default = f(THSEZ) or RHOTRE

This is the turbulence coherence length as defined by H. T. Yura. [Ref. 2C]. (see turbulence section for more discussion and references)

- V0 (m/sec)

The atmospheric wind. The direction of the wind is parallel and opposite to the direction of target motion. Note, in the present program, V0 is a constant independent of altitude.

- ACELCM (\*) 0.0 to 1.0

This parameter allows the user to correct for thermal blooming as if by adaptive optics. The value entered may range from 0.0 to 1.0. If 0.0 is used, complete thermal blooming compensation will occur. Conversely, if 1.0 is entered, no compensation will be applied. The variance of the phase distortion is multiplied by this correction factor before the Strehl relation is used to compute the relative intensity reduction due to thermal blooming.

$$\frac{I}{I_0} = \exp(-\sigma^2 * AOBLOM) \quad (3.4)$$

- AVGSFT (\*) 0.0 to 1.0

AVGSFT allows the user latitude in defining the far-field spot size to other than that indicated by GUTSAVG analysis. A value of 1.0 would result in the peak irradiance according to the program analysis. An entered value of .5, for example, would result in a peak irradiance 50% less than the program would otherwise indicate. AVGSFT, then, is an adjustment factor that allows the user to account for effects not addressed in the GUTSAVG propagation calculations.

- SIGJIT (radians)

SIGJIT is the  $2\sigma_p$  variance for pointing and tracking jitter.

- ADAP (\*) 0.0 to 1.0

This term is a correction factor for tilt due to turbulence. It represents the residual tilt after AO compensation. ADAP may be varied from 0.0 to 1.0. A value of 1.0 would result in no tilt due to turbulence being removed while a value of 0.0 would result in total tilt due to turbulence compensation. If full AO is selected the program will set ADAP equal to 0.0.

- NFLAGA (\*) 0 or 1

NFLAGA is a selection indicator for full zonal adaptive optics. Enter a 0 if AO is not desired, enter a 1 if AO is desired. If AO is used, XJT, BWIDTH, and NA must be specified.

• NCISC (\*) 0 or 1

NCISC is a selection indicator for isoplanatic calculations. Enter a 1 to inhibit isoplanatic calculations; enter a 0 if isoplanatic calculations are desired.

• XJT (Watts/sterad)

XJT is the target radiant intensity. It is one of the factors used to determine how noise affects the response of the AO system.

• BWIDTH (Hz)

BWIDTH is the bandwidth of the adaptive optics system.

• NA (\*)

NA is the number of AO actuators used to perform phase adjustment.

• AESICZ (\*)

This is the percent transmission at zenith at the sensing wavelength of the AO system. This term is used in the determination of relative noise at the AO sensor.

• N1 (\*)

The number of iteration steps for the angle loop of the program from THETMX to 0.

• N2 (\*)

The number of altitude intervals for absorption and scattering determination.

• N3 (\*)

The number of altitude intervals for the turbulence calculations.

• N4 (\*)

The number of iteration intervals for the MTF calculations.

• N5 (\*)

The number of intervals for the slant path update of thermal blooming.

## E. ENGAGEMENT GEOMETRY

The target engagement geometry is that of a earth-based transmitter and a target satellite at a given orbit. No attempt is made to define an engagement envelope based on threshold irradiance or fluence<sup>1</sup>. The input parameters defining the engagement window in GUTSAVG are THETMX, ICFE, and HSA1. The general geometry of this window is shown in Figure 3.1 . Only half of the total transit window is addressed in the program calculations; the results are the

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<sup>1</sup> The GUTSEP (fcctprint) version of guts was written to do this. Except for this feature, the propagation calculations are identical to GUTSAVG.

same for either half. The program output reflects this half-window evaluation except for parameters such as total fluence and shot time which are simply double the computed values.

Figure 3.2 defines the earth center angle (ECANG). ECANG is a function of the user input THETMX. Most of the geometric calculations are referenced to earth center. Therefore, this angle is used for computing such positioning data as the angle interval at which the irradiance will be evaluated (see Figure 3.3).

Offset flight paths require a coordinate translation as shown in Figure 3.4. Position and velocity relative to the transmitter are computed as in Figure 3.5. It should be noted that if the flight path is offset, the zenith angle will exceed THETMX for part or all of the window. This is because the window is defined in the x-z plane only.



$H_s$  - Zenith altitude of target

$\theta_m$  - Maximum zenith angle for engagement (zenith path)

$L_o$  - Offset distance

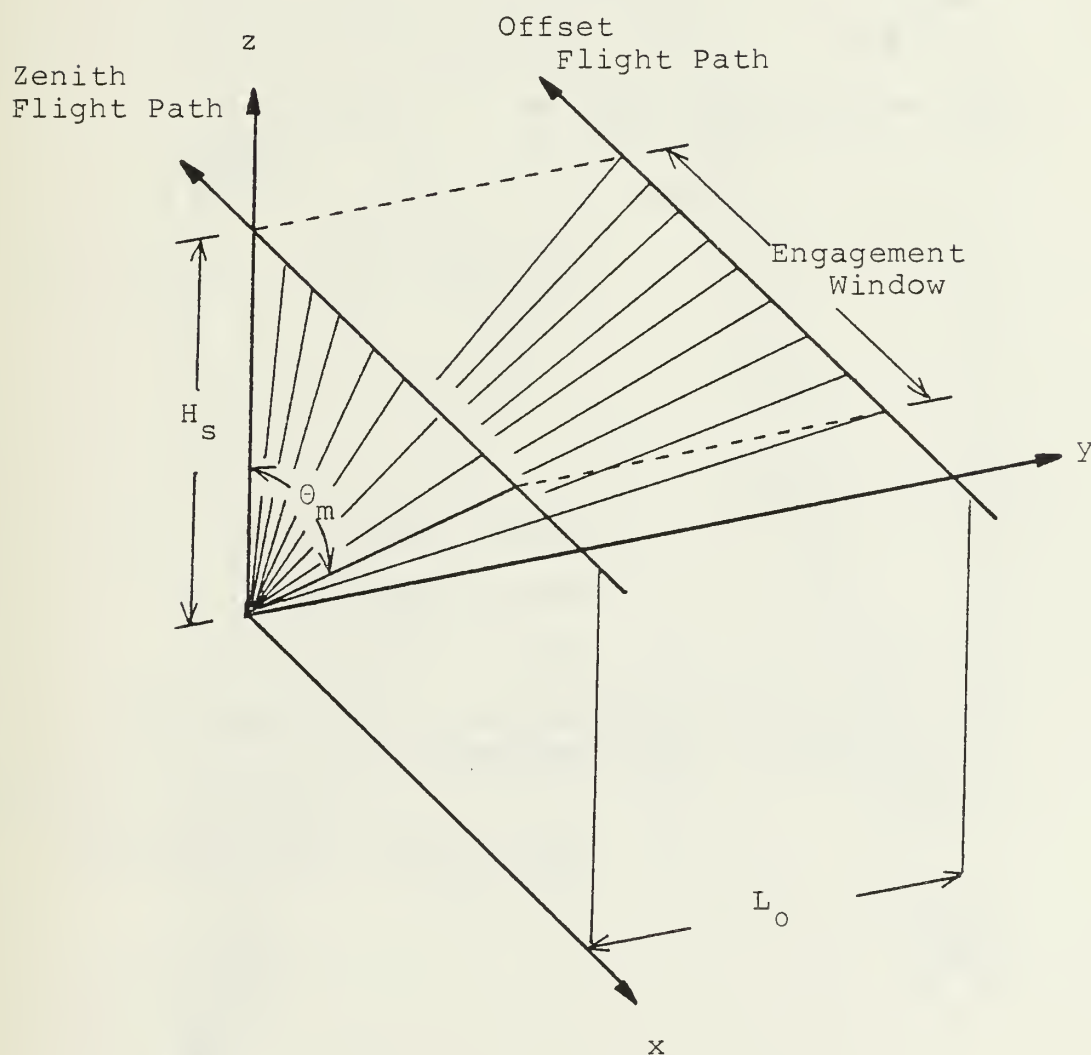


Figure 3.1 General Engagement Geometry.

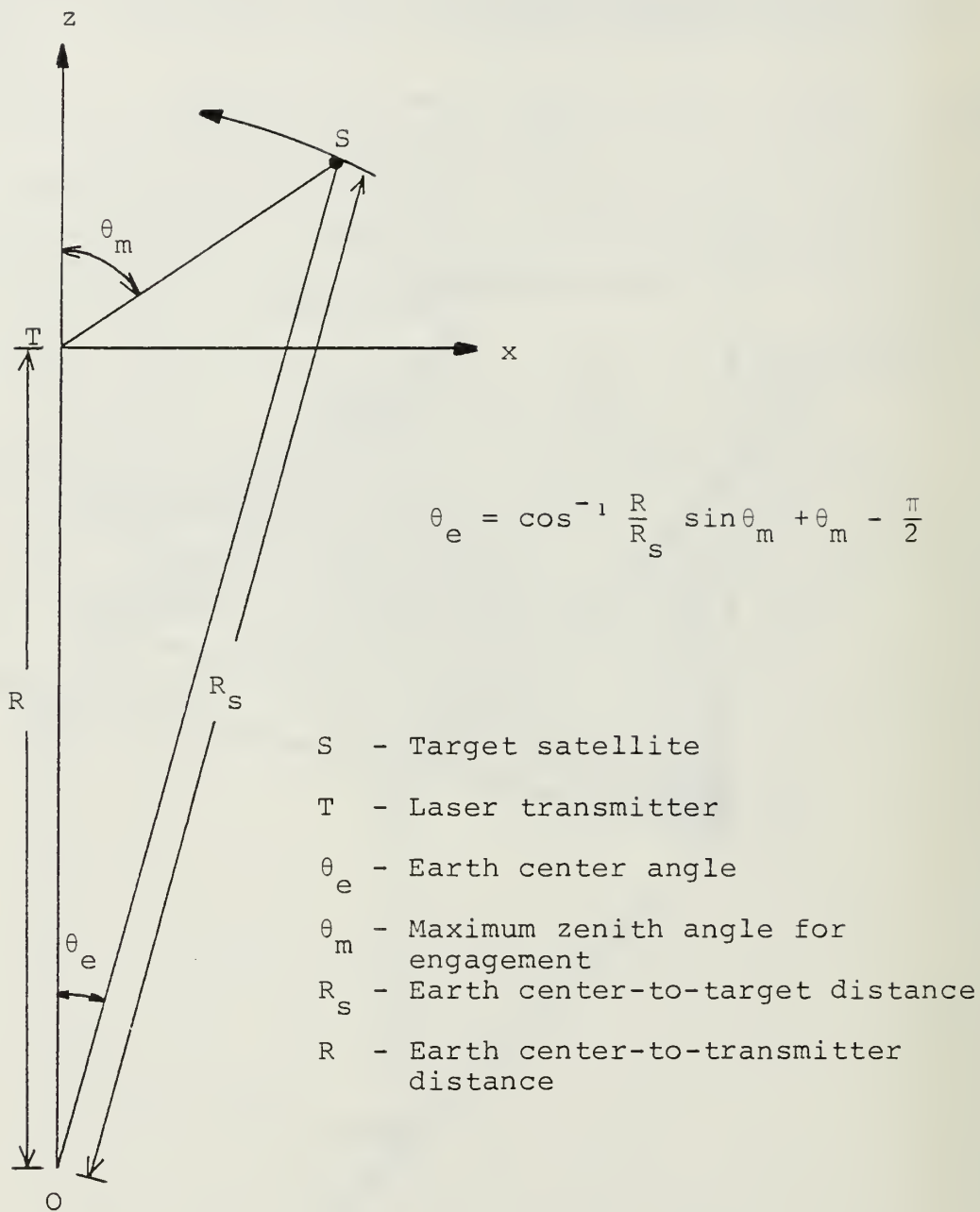


Figure 3.2 Earth Center Angle (ECANG).

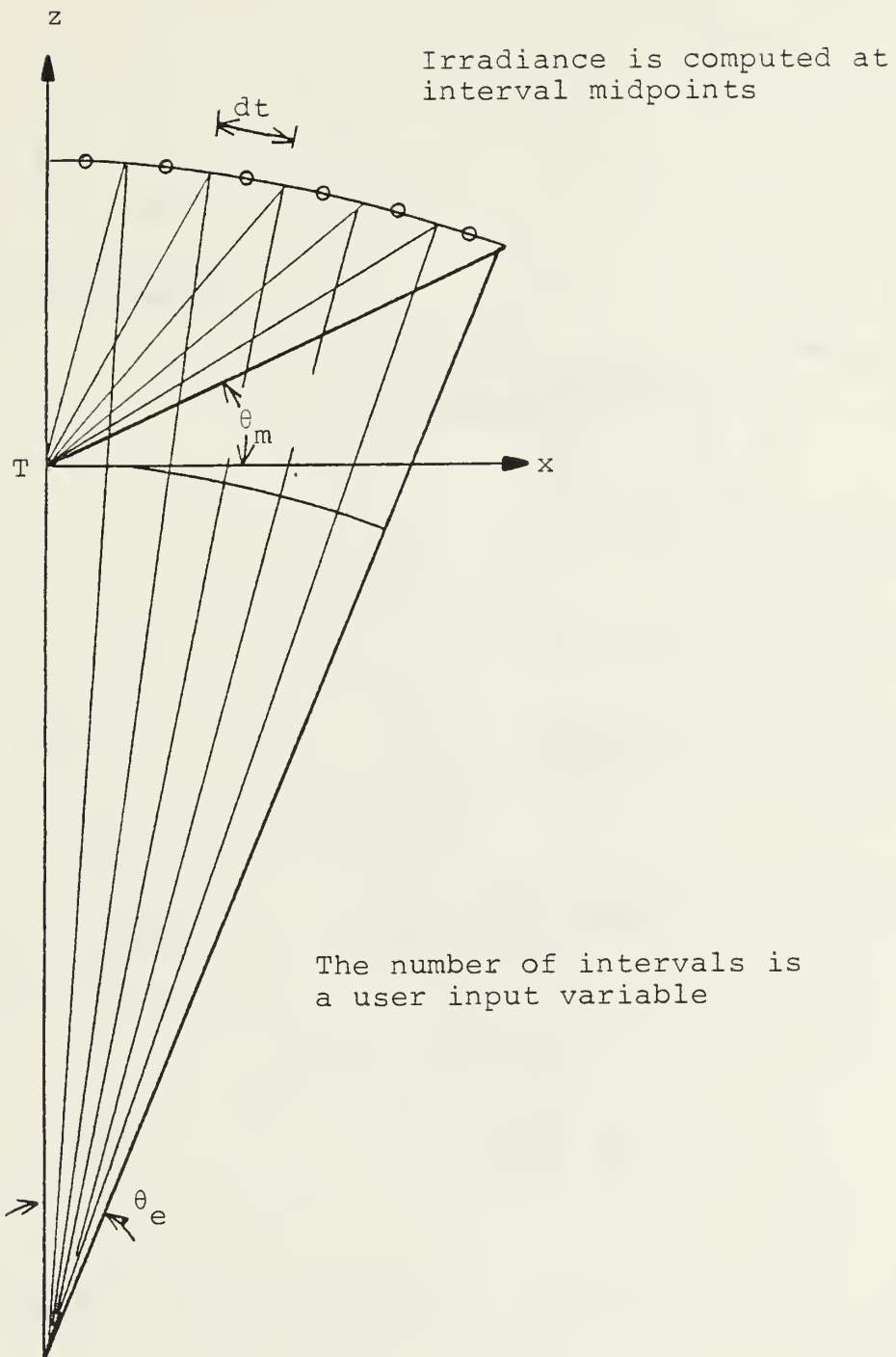


Figure 3.3 Angle Intervals for Irradiance Evaluation.

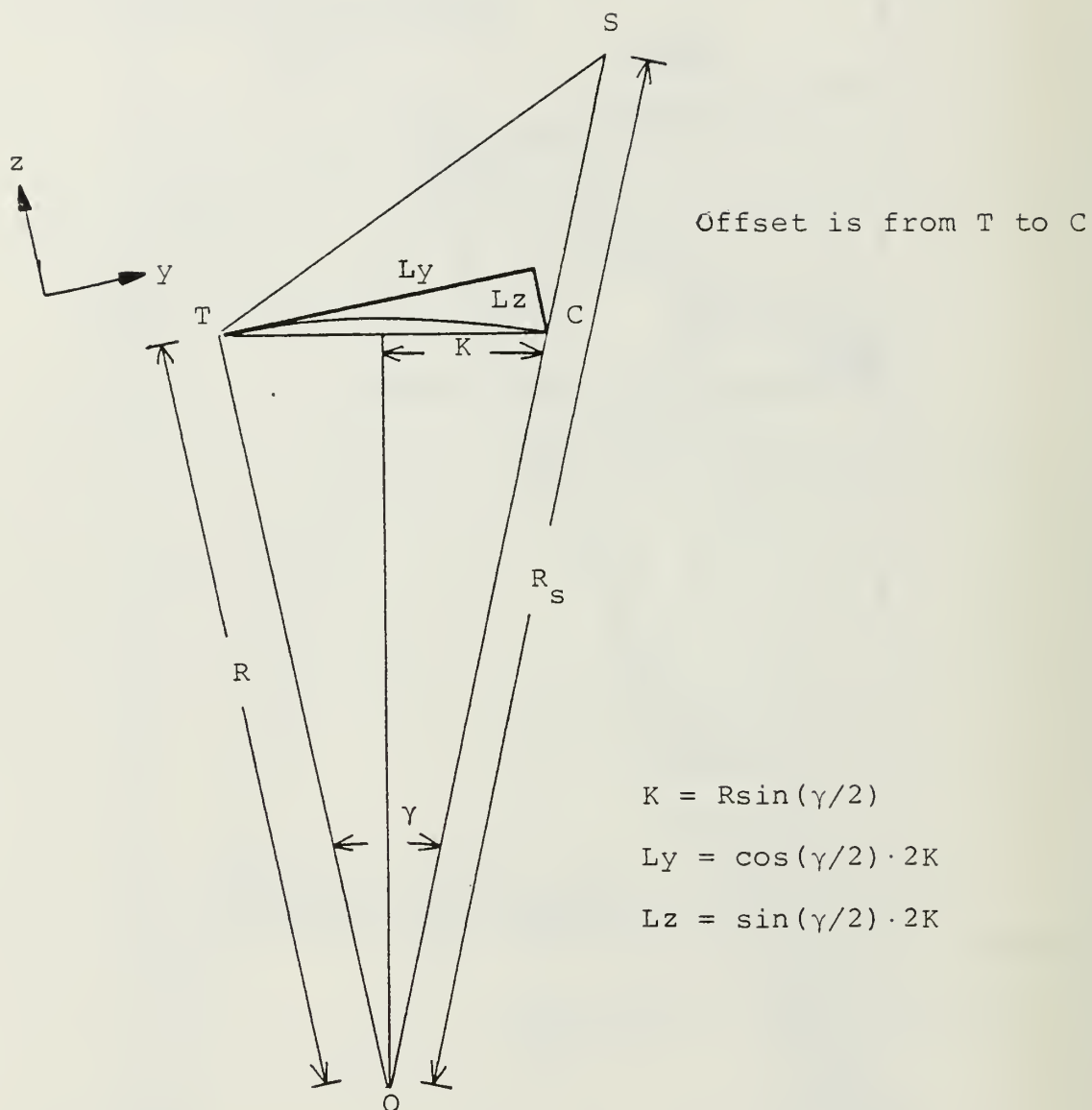
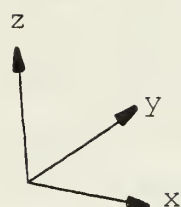


Figure 3.4 Coordinate Translation due to Flight Path Offset.

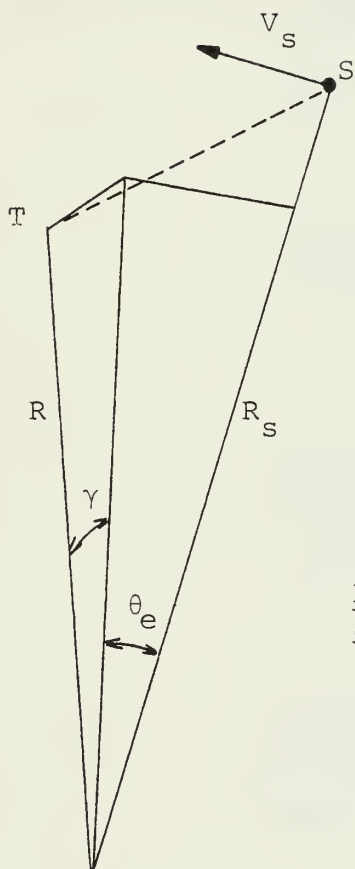


### Velocity components

$$V_x = -V_s \cos(\theta_e)$$

$$V_y = V_s \sin(\theta_e) \cos(\gamma)$$

$$V_z = V_s \sin(\theta_e) \sin(\gamma)$$



### Position

$$X = R_s \sin(\theta_e)$$

$$Y = L_y \cdot \cos(\gamma) + (Z_0 - R - L_z) \cdot \sin(\gamma)$$

$$Z = -L_y \cdot \sin(\gamma) + (Z_0 - R - L_z) \cdot \cos(\gamma)$$

$$\text{where } Z_0 = R_s \cos(\theta_e)$$

### Range from transmitter(T) to satellite(S)

$$R_{ts} = Z + X + Y$$

(For  $L_y$  and  $L_z$  definition, see Figure 3.4)

**Figure 3.5 Velocity and Position Relative to Transmitter.**

### C. MAIN PROGRAM FLOW DIAGRAM

The main program mostly consists of geometry calculations and decision flow points. The decision points allow branching to adaptive optics and isoplanatic subroutines. Most of the propagation calculations are done within the subroutines. Only two major iteration loops reside in the main program, the angle interval loop and the combined MTF integrative loop. The following is a general flow diagram for the main program. Decision variables are user inputs or program defined parameters.

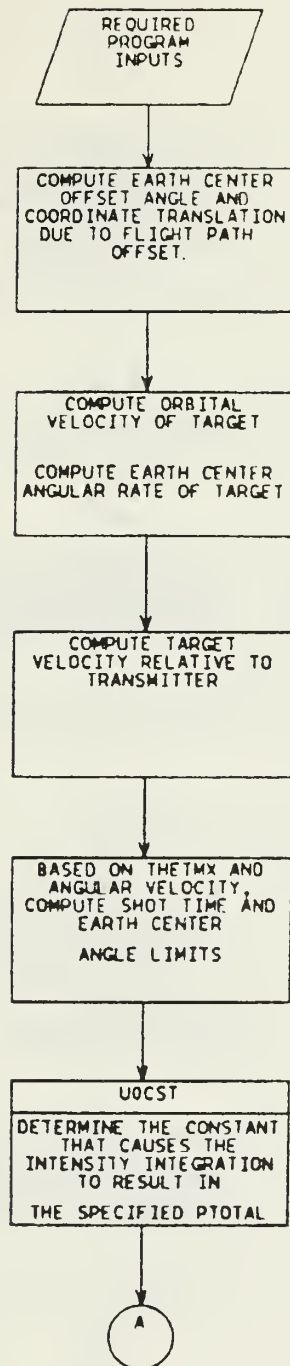


Figure 3.6 Main Program Flow Diagram.



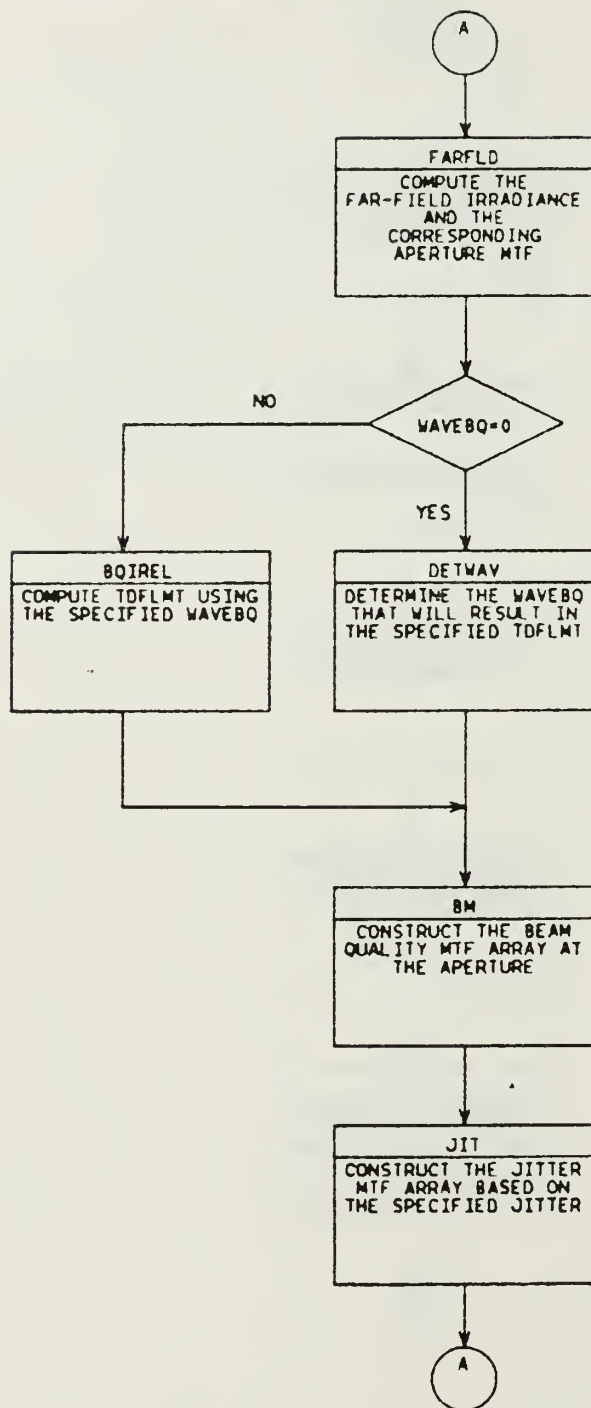


Figure 3.7 Main Program Flow Diagram (cont).



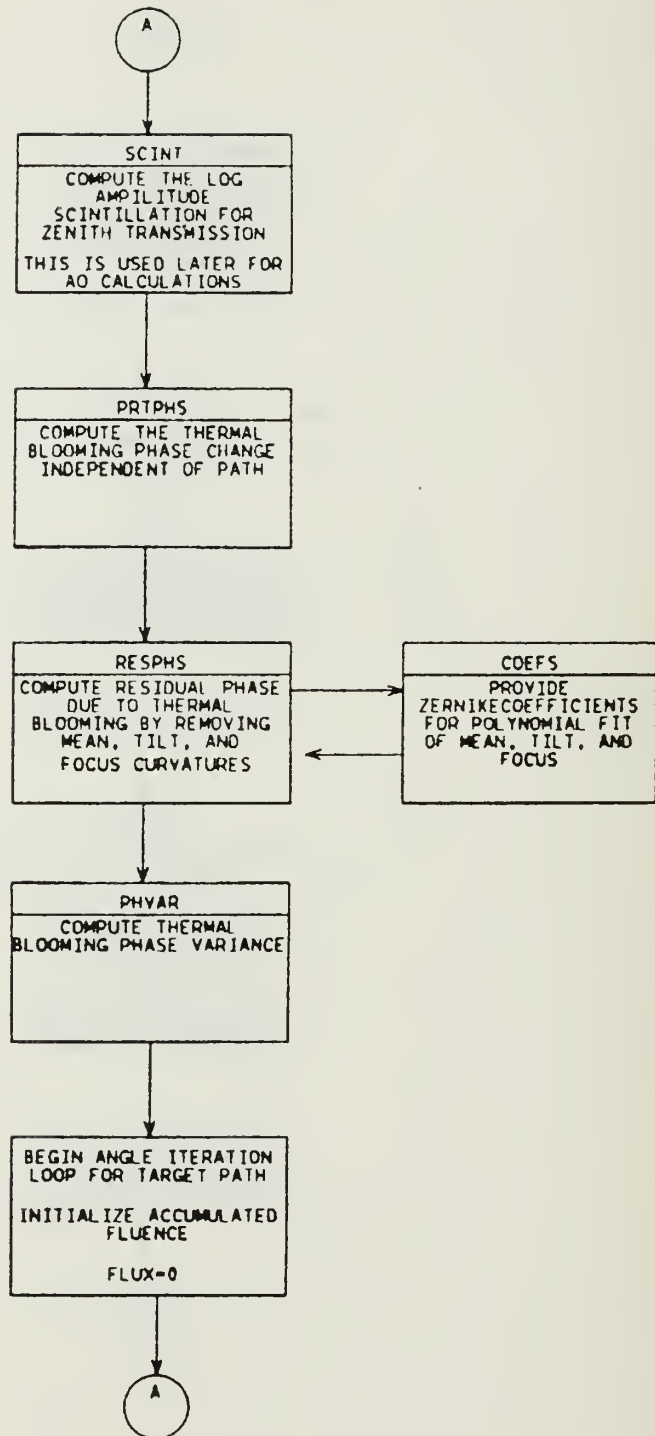


Figure 3.9 Main Program Flow Diagram (cont).

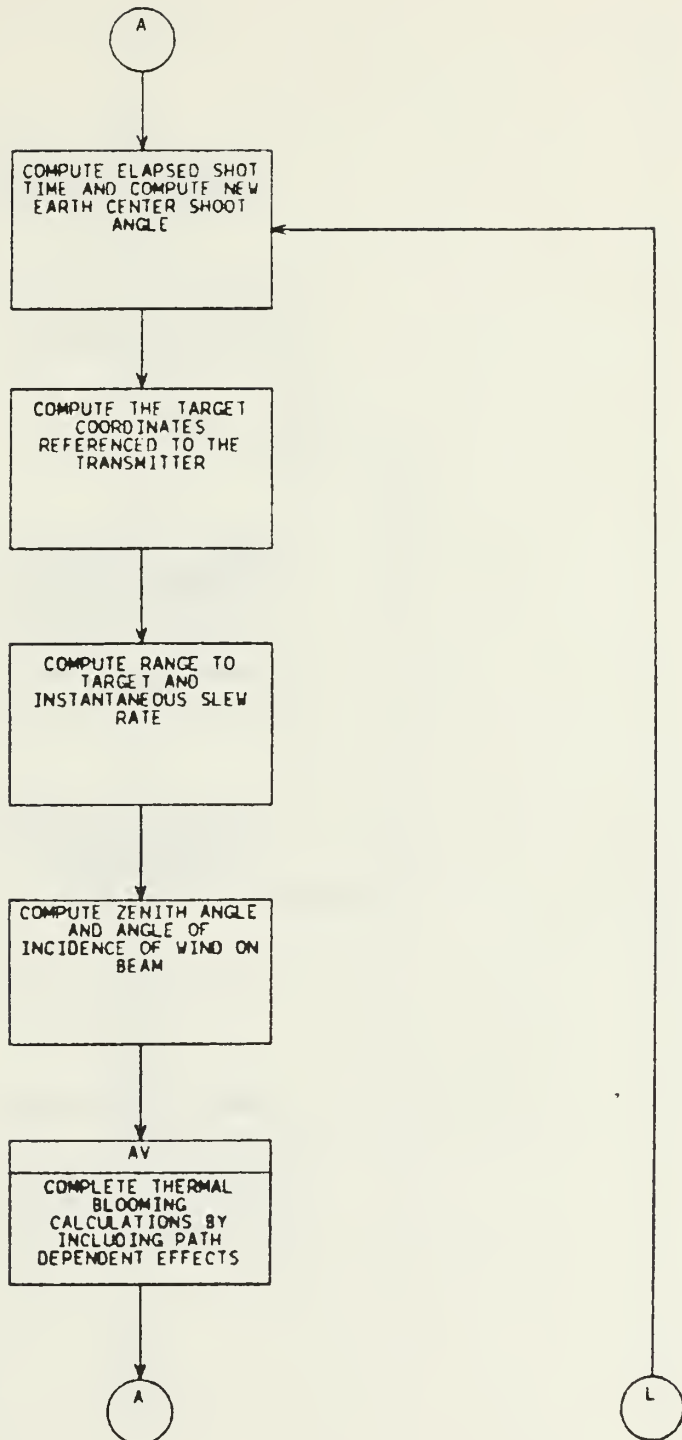


Figure 3.10 Main Program Flow Diagram (cont).

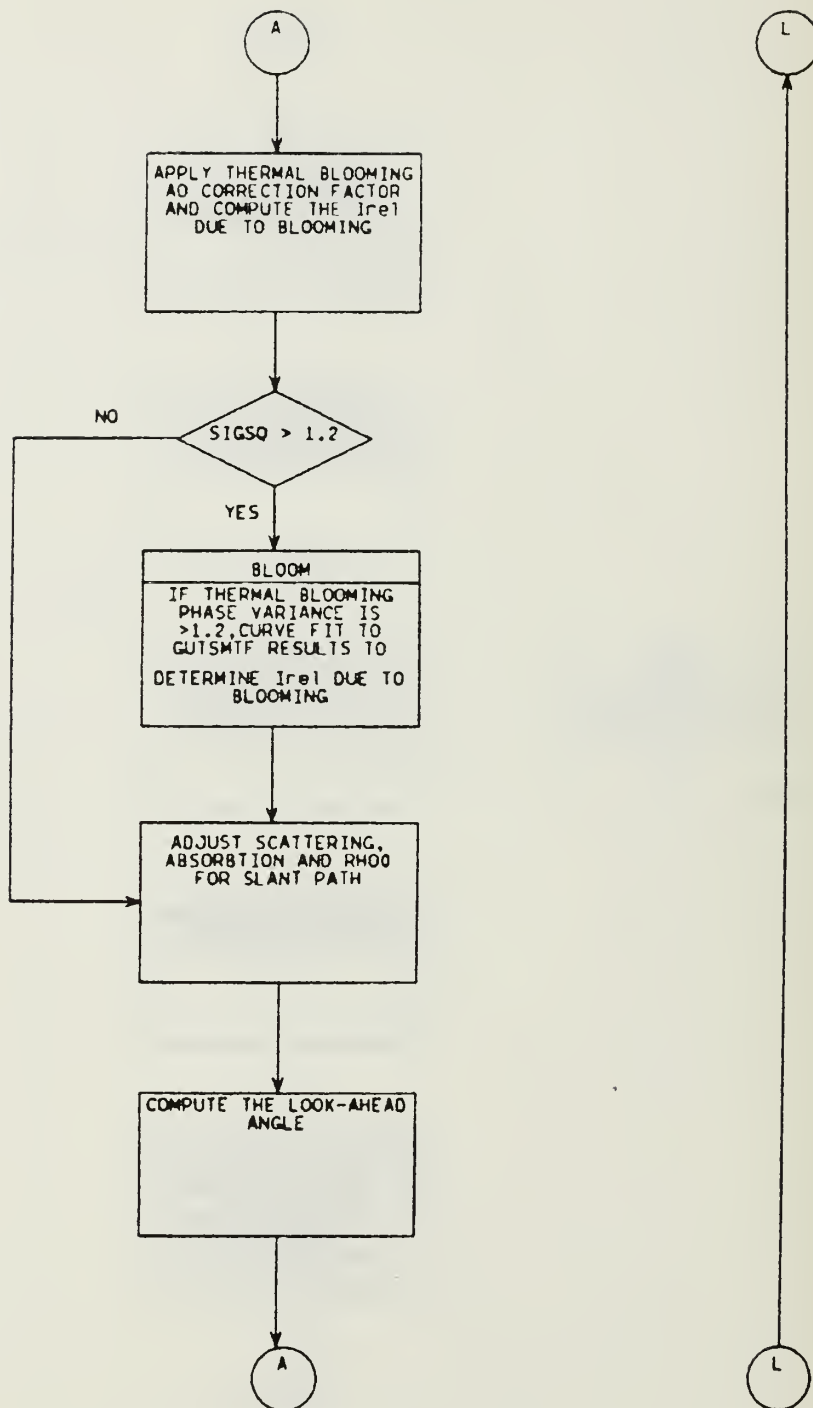


Figure 3.11 Main Program Flow Diagram (cont).

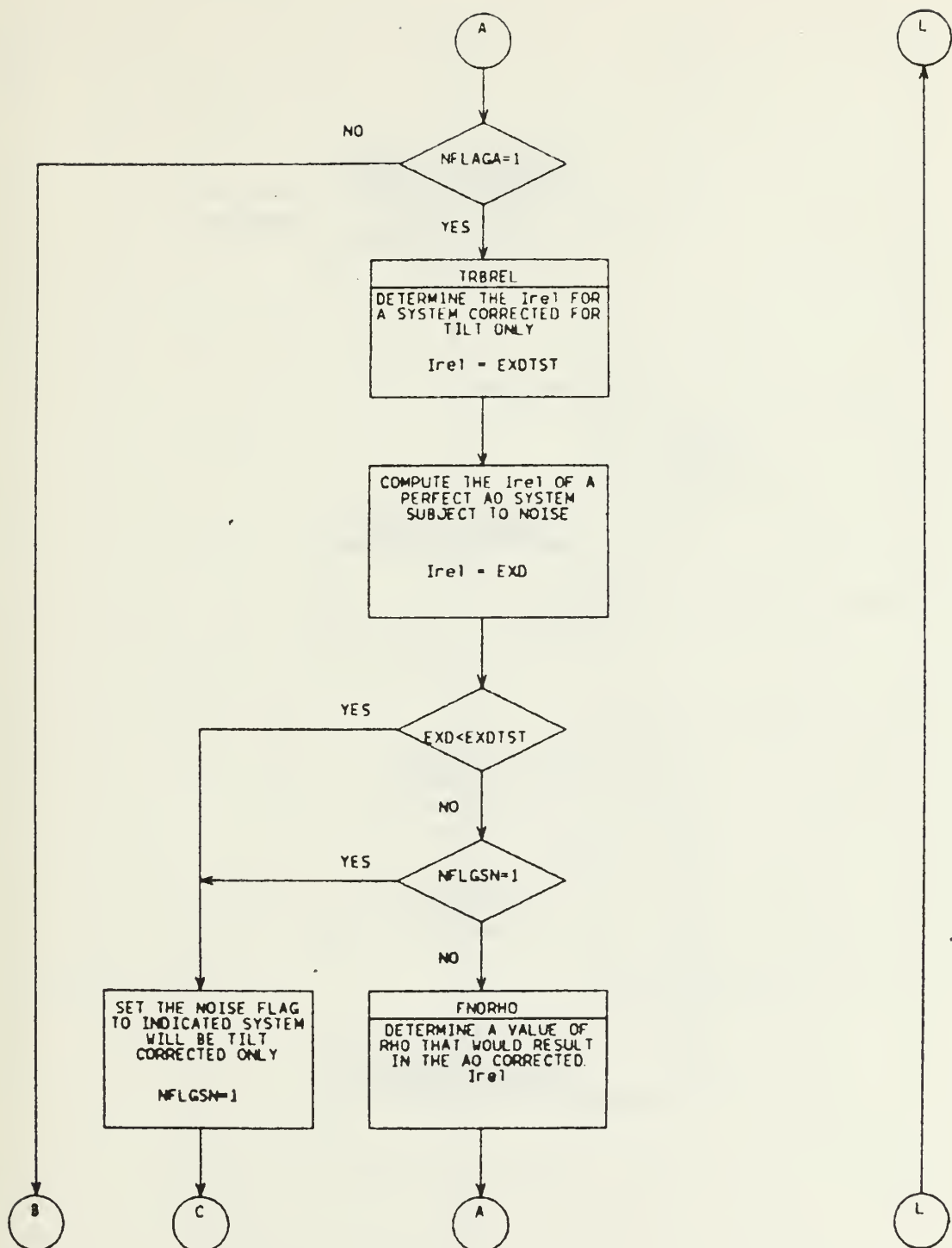


Figure 3.12 Main Program Flow Diagram (cont).

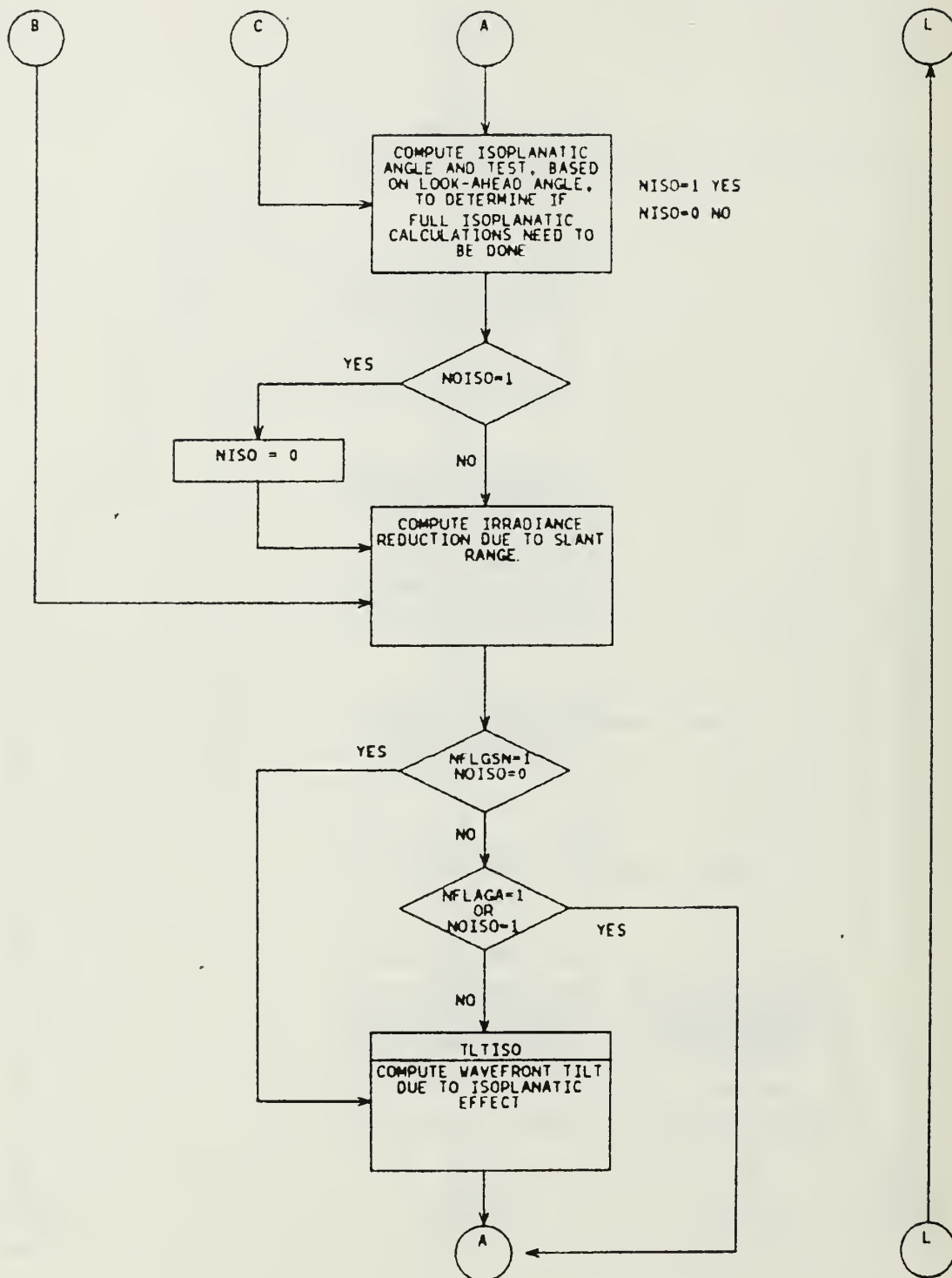


Figure 3.13 Main Program Flow Diagram (cont).





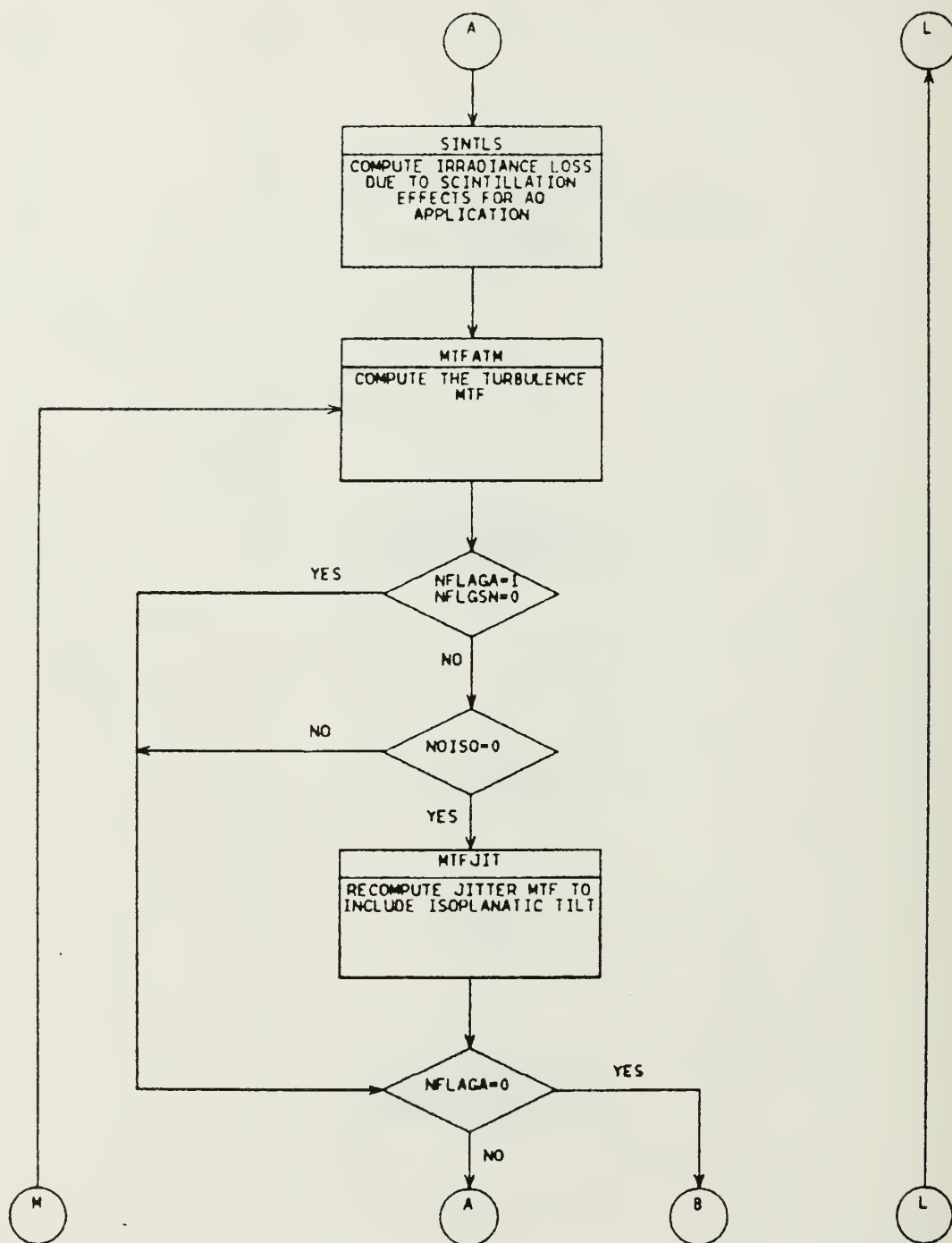


Figure 3.14 Main Program Flow Diagram (cont).

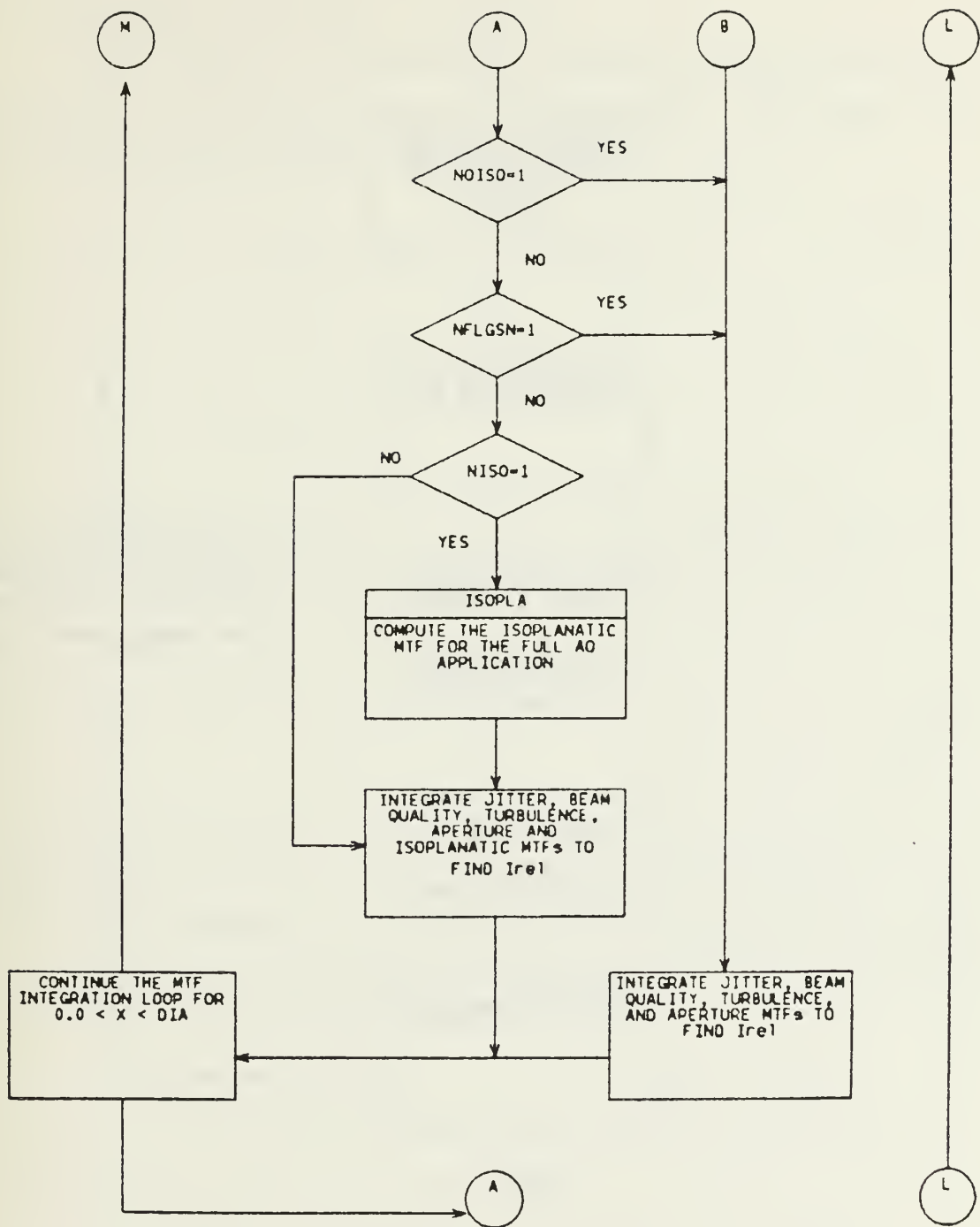


Figure 3.15 Main Program Flow Diagram (cont).

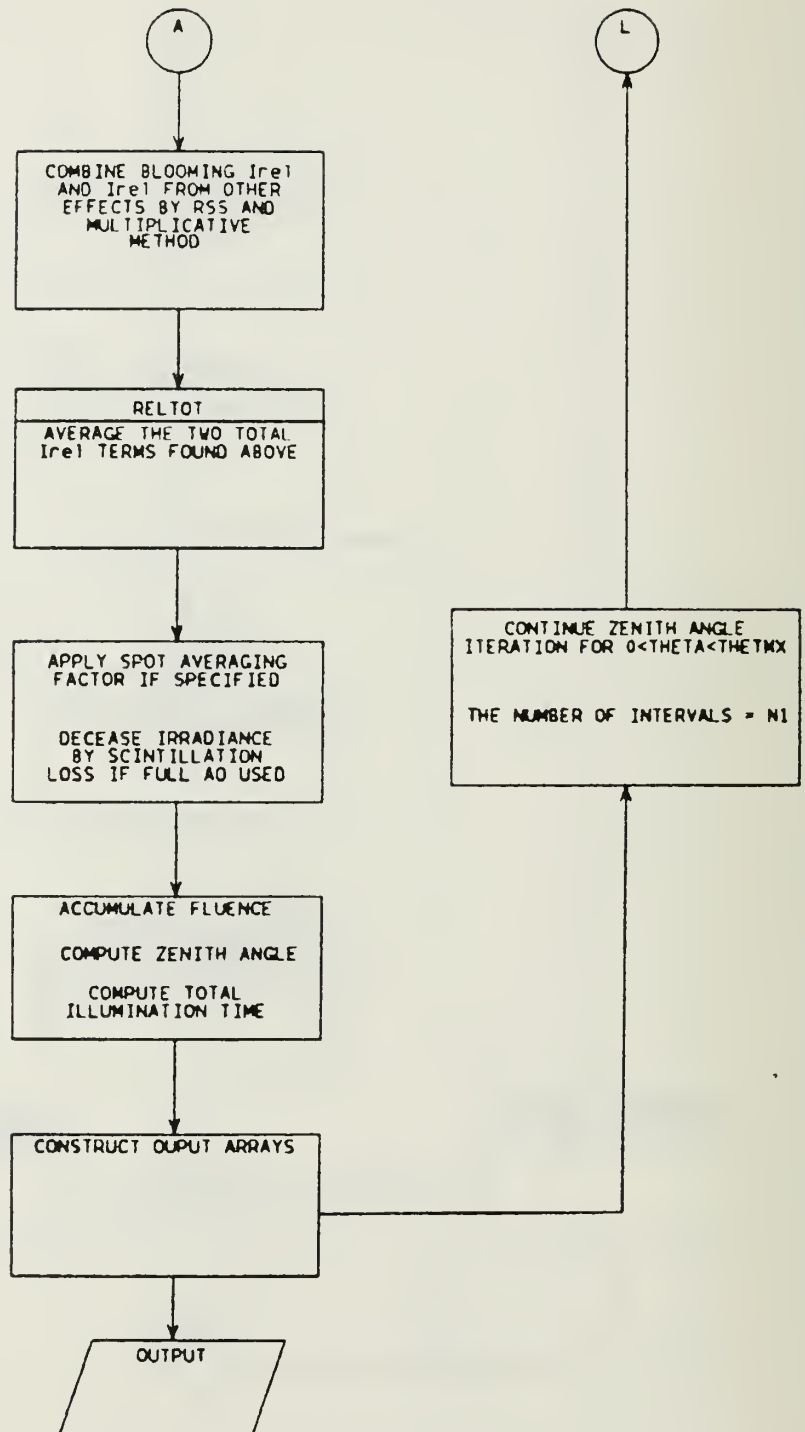


Figure 3.16 Main Program Flow Diagram (cont).

## D. SUBROUTINE DESCRIPTION

### 1. AESCRB and SCAT

As noted in the preceding chapter, absorption and scattering effects are treated indentially. The AESCRB and SCAT algorithms perform the integration

$$T_a = \exp - \int_{h_t}^{h_{atm}} \alpha(h) dh \quad (3.5)$$

$$T_s = \exp - \int_{h_t}^{h_{atm}} \sigma(h) dh \quad (3.6)$$

The result is the transmission due to the total absorption or total scattering. The correction for slant range is applied within the angle interval loop of the main program and is simply

$$T = T^{(\sec \theta)} \quad (3.7)$$

is the zenith angle of the target with respect to the transmitter.

The extinction coefficients for absorption ( $\alpha$ ) and for scattering ( $\sigma$ ) are provided to the subroutines by a call to routines ALFA and ALFS respectively.

TABLE I  
AESCRB and SCAT Program Variable Definitions

<u>Variable</u>	<u>Fortran name</u>		<u>Definition</u>
	<u>Sub</u>	<u>Main</u>	
$T_a$ (AESCRB)	T	TABSC	Total molecular transmission
$T_s$ (SCAT)	T	TSCAIO	Total scattered transmission
$h_{atm}$ (meters)	HATMC	HATMC	Height of atmosphere
$h_t$ (meters)	HT	HTRANS	Height above MSI of transmitter
$\alpha(h)$ $(km)^{-1}$	ALP	-	Absorption coef. at given altitude
$\sigma(h)$ $(km)^{-1}$	ALS,	-	Scattering coef at given altitude
-	N	N2	# of integration intervals

## 2. ALFS and ALFA

These two routines are also identical. They provide the extinction coefficients to ABSORB and SCAT for a specified altitude. At each altitude where a coefficient value is desired, a linear interpolation is performed between data points supplied by the user. Data statements precede each of these subprograms, and it is with these statements that the absorption and scattering data should be entered. Units for the coefficient and corresponding altitude should be  $km^{-1}$  and km respectively.

TABLE II  
ALFS and ALFA Program Variables and Definitions

<u>Variable</u>	<u>Fortran name</u>		<u>Definition</u>
	<u>Sub</u>	<u>Main</u>	
$\sigma(h) \text{ (km)}^{-1}$	S	ALS	Scattering coef. at specified altitude
$\alpha(h) \text{ (km)}^{-1}$	A	ALF	Absorption coef. at specified altitude
h (meters)	H	-	specific altitude
—	ALT (NL)	-	Altitude data list
—	ATA (NL)	-	Absorption data list
—	ATS (NL)	-	Scattering data list
—	NL	-	Number of points in data list

### 3. UOCST

For a gaussian beam with constant phase, the initial amplitude distribution at the transmitter aperture is

$$U(r) = U_0 \exp \left[ -(r/w)^2 \right] \quad (3.8)$$

where  $U_0$  is the amplitude and  $w$  is the spot size [Ref. 21]. The purpose of UOCST is to compute the constant  $U_0$  for a given aperture power.

By the scalar wave approximation, the intensity distribution is [Ref. 22]



$$I(r) = |U(r)|^2 \quad (3.9)$$

To relate the field distribution to the power, the intensity distribution is integrated over the aperture.

$$P_t = \pi \int_{r_i}^{r_o} I(r) dr^2 \quad (3.10)$$

Substituting 3.8 and 3.9 into 3.10

$$P_t = \pi \int_{r_i}^{r_o} U_0 \exp[-(r/w)^2] dr^2 \quad (3.11)$$

then rearranging terms, produces the expression for  $U_0$ .

$$U = \left[ P_t \left\{ \pi \int_{r_i}^{r_o} \left( \exp[-(r/w)^2] \right)^2 dr^2 \right\}^{-1} \right]^{\frac{1}{2}} \quad (3.12)$$

The integration limits  $r_o$  and  $r_i$  are the radius of the transmitter and the obscuration, respectively.

UOCST performs the integration in 3.12 using the trapezoidal rule. A call is made to subroutine FIELD to evaluate  $\exp[-(r/w)^2]$  which is simply  $U(r)$  with  $U_0 = 1$ . For this reason,  $U_0$  is defined as unity when FIELD is called by UOCST.

TABLE III  
UOCST Program Variables and Definitions

<u>Variable</u>	<u>Fortran</u>	<u>name</u>	<u>Definition</u>
	<u>SUB</u>	<u>Main</u>	
$U_0 \text{ (W)}^{\frac{1}{2}} \text{m}^{-1}$	U0	-	Normalization constant
$P_t \text{ (Watts)}$	P	PICTAL	Total aperture exit power
-	N	MI	# of integration increments
$r_0 \text{ (meters)}$	RO	-	Outer radius of transmitter
$r_i \text{ (meters)}$	RI	-	Radius of obscuration
$U(r) \text{ (W)}^{\frac{1}{2}} \text{m}^{-1}$	UR	-	Field amplitude at radius r
$w \text{ (meters)}$	BMRAI	-	Radius of spot at aperture

#### 4. FIELD

FIELD calculates the field distribution for a axis-symmetric Gaussian beam with constant phase.

$$U(r) = U_0 \exp \left[ -(r/w)^2 \right] \quad (3.13)$$

TABLE IV  
FIELD Program Variable Definitions

<u>Variable</u>	<u>Fortran name</u>		<u>Definition</u>
	<u>Sub</u>	<u>Main</u>	
$U(r) (W)^{\frac{1}{2}} m^{-1}$	UR	-	Field amplitude at r
$U_0 (W)^{\frac{1}{2}} m^{-1}$	UO	-	Normalization constant
$w$ (meters)	BMRAI	-	Radius of spot at aperture

### 5. FARFIELD

In the Fraunhofer region, the amplitude distribution can be found by taking the Fourier transform of the aperture distribution [Ref. 23]. Using polar coordinates and noting axial symmetry,  $U(\rho)$  in the far-field can be expressed as

$$U(\rho) = \frac{1}{\lambda z} \int_a^b \int_0^{2\pi} U(r) \exp \left[ - \left( \frac{i 2 \pi}{\lambda z} \right) \cdot r \rho \cdot \cos \theta \right] r dr d\theta \quad (3.14)$$

Using integral relation for the zero order Bessel function, equation 3.14 can be simplified to [Ref. 24]

$$U(\rho) = \frac{2\pi}{\lambda z} \int_a^b U(r) J_0 \left( \frac{2\pi \rho r}{\lambda z} \right) r dr \quad (3.15)$$

The intensity in the far-field is then given by  $I(r) = |U(r)|^2$  or in terms of equation 3.15

$$I(\rho) = \left( \frac{2\pi}{\lambda z} \right)^2 \left[ \int_a^b U(r) J_0 \left( \frac{2\pi \rho r}{\lambda z} \right) r dr \right]^2 \quad (3.16)$$

where  $b$  and  $a$  are the radius of the transmitter and the radius of the obscuration, respectively. [Ref. 25]

FARFIELD evaluates 3.16 at a specified number of increments in the far-field and assigns these values to an array  $F(i)$ .  $F(i)$  is normalized with the total aperture power so that the MTF produced would be unity at the origin. Note, however, that when the MTF is computed in this case, the MTF is normalized so as to produce an  $I_{rel}$  (intensity relative) value when integrated.

$$M_a(\bar{\rho}) = \frac{2\pi}{\lambda z} \frac{P_t}{I_0} \int_0^r I(\bar{\rho}) J_0 \left( \frac{2\pi \bar{\rho} r}{\lambda z} \right) \bar{\rho} d\bar{\rho} \quad (3.17)$$

$I_0$  is determined by evaluating equation 3.16 with  $r=0.0$ .

TABLE V  
FARFLD Program Variables and Definitions

<u>Variable</u>	<u>Fortran</u>	<u>name</u>	<u>Definition</u>
	<u>Sub</u>	<u>Main</u>	
$k(m)^{-1}$	CKR	-	$(2\pi/\lambda)$
$\rho$	R1	-	Radius in far-field
$r$	R0	-	Radius in aperture
$I_0$ (Watts)	PMAX0	PMAX0	Far-field on-axis intensity for a diffraction limited beam
$I(r)$ ( $W/m^2$ )	F(I)	TISC	Irradiance in far-field
$M_a(\bar{\rho})$	G(I)	IRRMTF	Aperture MTF
-	DX2	DX	Aperture MTF increments
$P_t$ (Watts)	P	PTOTAL	Total power in the aperture

## 6. FCIFEL

If the 'times diffraction limited number' (TDFLMT) is not specified, this routine computes the Irel value due to beam quality which is then used to compute TDFLMT in the main program. The calculation performed is

$$Irel = 2\pi \int M_a(\bar{\rho}) M_b(\bar{\rho}) \bar{\rho} d\bar{\rho} \quad (3.18)$$

where  $M_a$  is the aperture MTF and  $M_b$  is the MTF for the beam quality phase screen.  $M_a$  is defined in subroutine FARFLD so that this integration produces an Irel value.  $M_b$  is the beam

quality MTF as computed by subroutine MTFBQ. TDFLMT is computed in the main program and is 1/ Irel .

TABLE VI  
EQIREL Program Variables and Definitions

<u>Variable</u>	<u>Fortran name</u>		<u>Definition</u>
	<u>Sub</u>	<u>Main</u>	
N	-	TDFLMT	Times diff. limited #
Irel	REL	TEQ	-
$M_a(\bar{\rho})$	A(I)	IRRMIF	Aperture MTF
$M_b(\bar{\rho})$	F(I)	-	MTF for phase screen
-	N4	N4	# of iterations for MTF calculations

## 7. DETWAV

If the RMS phase distortion parameter (WAVEBQ) is not specified, this routine computes it based on the approximation

$$\text{Irel} = \exp(-\sigma^2) \quad (3.19)$$

where  $\sigma = \frac{2\pi\delta_{\text{rms}}}{\lambda}$  and  $\delta_{\text{rms}}$  is the RMS value of the phase distortion at the aperture. Irel is the intensity degradation due to beam quality and is equal to  $1/(N)^2$ . N is the input parameter TDFLMT. DETWAV first evaluates  $\sigma^2$  using equation 3.19 and then uses this value as a starting point

to compute a more accurate  $\sigma^2$  by iteration using subroutine EQIREL.  $\sigma^2$  is used to compute the beam quality MTF and the beam quality Irel as in equation 3.18.  $\sigma^2$  is adjusted, and the process repeated until the Irel found by equation 3.18 is equal to that determined by  $1/(N)^2$ .

TABLE VII  
DETNAV Program Variables and Definitions

<u>Variable</u>	<u>Fortran Name</u>		<u>Definition</u>
$\left[ \frac{2\pi\delta_{rms}}{\lambda} \right]^2$	<u>SUB</u>	<u>MAIN</u>	
	VAREQ	VAREQ	Constant
$\frac{\delta_{rms}}{\lambda}$	WAVEEQ	WAVEEQ	phase distortion parameter
$1/N^2$	RELO	-	$1/(IDFLMT)^2$

#### 8. MTFEQ and BM

These two routines calculate the beam quality MTF array. The MTF is [Ref. 26]

$$M_b(\bar{\rho}) = \exp\left(-k^2 \left[\sigma^2 - C_\phi(\bar{\rho})\right]\right) \quad (3.20)$$

where  $C_\phi(\rho)$  is the autocorrelation function of the phase and is the phase variance.  $C_\phi(\rho)$  is assumed to be Gaussian. Letting  $C_\phi(\rho) = \sigma^2 \exp[-(\rho/L)^2]$ , where L is the phase correlation length, results in [Ref. 27]



$$M_b(\bar{\rho}) = \exp \left[ - \left( \frac{2\pi\delta_{\text{rms}}}{\lambda} \right)^2 \left( 1 - \exp \left[ - (\bar{\rho}/L)^2 \right] \right) \right] \quad (3.21)$$

$\frac{\delta_{\text{rms}}}{\lambda}$  is the wavelength RMS phase distortion and is an input parameter (WAVEEQ). L, also a user input (SCALEQ), will default to 1/5 the diameter of the aperture if not otherwise specified.

TABLE VIII

MTFEQ and BM Program Variables and Definitions

<u>Variable</u>	<u>Fortran name</u>		<u>Definition</u>
	<u>SUB</u>	<u>MAIN</u>	
$\left[ \frac{2\pi\delta_{\text{rms}}}{\lambda} \right]^2$	VAREQ	VAREQ	Beam quality variance
$M_b(\bar{\rho})$	F(I)	BQMTF	Beam quality MTF
-	N4	N4	# of MTF integration increments
$k \text{ (m)}^{-1}$	-	-	$(2\pi/\lambda)$

## 9. ISOTRB

ISOTRB calculates the zenith isoplanatic angle for use in the adaptive optics portion of the program. The angle is given by [Ref. 28]

$$\theta_0 = .314 \left[ \frac{2.91}{6.88} \sec\theta \int_{h_t}^{h_{atm}} C_n^2(h) h^{5/3} dh \right]^{-3/5} \quad (3.22)$$

For the rear zenith case,  $\sec\theta=1$ .  $C_n^2$  is the refractive index structure constant and is calculated by subroutine CN2H as function of altitude. See Fried [Ref. 29] for a discussion of the above angle.

TABLE IX  
ISOTRB Program Variables and Definitions

<u>Variables</u>	<u>Fortran</u> <u>Sub</u>	<u>Name</u> <u>Main</u>	<u>Definition</u>
$\theta_0$ (rad)	ISOANG	ISCAN0	Zenith isoplanatic angle
$C_n^2 (h)^{-2/3}$	CN2	-	Refractive index structure constant
-	N	N3	Integration intervals for turbulence
$\theta$ (deg)	-	OMEGA	Zenith angle

## 10. SCINT and SINILS

If full adaptive optics are used, amplitude scintillation effects will act to degrade the performance of the

conventional phase correcting adaptive optics system. This subroutine computes the log amplitude variance of the scintillations for zenith transmission. The approximation used is

$$\sigma_z^2 = .56k \int_{h_t}^{h_{atm}} h^{5/6} C_n^2(h) dh \quad (3.23)$$

For the off zenith case

$$\sigma_z^2 = \sigma_z^2 \sec(\theta) \quad (3.24)$$

where  $\theta$  is the zenith angle [Ref. 30]. The relative irradiance loss due to scintillation is

$$\text{AMP LOSS} = \exp\left(-\sigma_z^2 \sec(\theta)\right) \quad (3.25)$$

The correction for the off zenith case is applied in subroutine SINILS in the angle loop of the main program when full adaptive optics are specified. This loss factor has been shown to be limited to approximately .55, therefore, a default value is used in the main program in the case where equation 3.25 yields a value less than 0.5 [Ref. 31].

TABLE X  
SCINTLS and SCINT Program variables and Definitions

<u>Variable</u>	<u>Fortran</u> <u>Sub</u>	<u>Name</u> <u>Main</u>	<u>Definition</u>
$k \text{ (m)}^{-1}$	CK	-	$2\pi/\lambda$
$C_n^2 \text{ (m)}^{-2/3}$	CN2H	-	Refractive index structure constant
$\sigma_x^2$	SIGXZ	SIGXZ	Log amplitude variation
Amf loss	TAMP	TAMP	Loss caused by scintillation

#### 11. CN2H

CN2H computes the index of refraction structure constant as a function of altitude.  $C_n^2$  is determined using Hufnagel's model with an added term to include the near surface effects. [Ref. 32] [Ref. 33]

$$C_n^2 = (5.94 \times 10^{-53}) h^{10} \exp\left(\frac{-h}{1000}\right) + (2.7 \times 10^{-16}) \exp\left(\frac{-h}{1500}\right) + (10^{-14}) \exp\left(\frac{-h}{100}\right) \quad (3.26)$$

Here, the units of  $h$  are meters.

#### 12. FHCTRE

This subroutine computes Yura's [Ref. 34] lateral coherence length,  $\rho_0$ , in terms of Fried's [Ref. 35] coherence diameter,  $r_0$ .

$$\rho_0 = r_0/2.1 \quad (3.27)$$

Substituting Fried's definition for  $r_0$

$$\rho_0 = \frac{1}{2.1} \left[ \frac{2.91}{6.88} k^2 \int_{h_t}^{h_{atm}} C_n^2(h) dh \right]^{-3/5} \quad (3.28)$$

TABLE XI  
RHOTRB Program Variables and Definitions

<u>Variable</u>	<u>Fortran</u>	<u>Name</u>	<u>Definition</u>
	<u>Sub</u>	<u>Main</u>	
$k \text{ (m)}^{-1}$	CK	-	$2\pi/\lambda$
$C_n^2 \text{ (m)}^{-2/3}$	CN2	-	Refractive index structure constant
$\rho_0 \text{ (meters)}$	RHC	RECO	Coherence length
-	N	N3	# of integration intervals for turbulence

### 13. JIT and MTFJIT

JIT AND MTFJIT function algorithmically the same as EM and MTFEQ. Together, they compute the jitter MTF array. MTFJIT is called by JIT for each radial increment. The jitter MTF is given by

$$M_j(\bar{\rho}) = \exp\left(\frac{k^2 \bar{\rho}^2 (2\sigma_p)^2}{8}\right) \quad (3.29)$$

where  $2\sigma_p$  is a user specified input. As with beam quality, this quantity is applied at the aperture.

TABLE XII  
JIT and MTFJIT Program Variables and Definitions

<u>Variable</u>	<u>Fortran</u>	<u>Name</u>	<u>Definition</u>
	<u>Sub</u>	<u>Main</u>	
$k (\text{m})^{-1}$	CK	-	$2\pi/\lambda$
$\epsilon_j(\rho)$	F	JITMTF	Jitter MTF

#### 14. FRFHS

This subroutine calculates that part of thermal blooming not dependent on the slant path of the beam. The equation used by GUTSAVG for the phase distortion due to thermal blooming is

$$\Delta\phi(x,y) = \left[ \frac{2\pi}{\lambda} \frac{n-1}{p_0} \frac{\gamma-1}{\gamma} \int_{-\infty}^{x'} I(x',y) dx' \right] \times \left[ \frac{\int_{h_t}^{h_{atm}} \alpha(h) \exp\left(-\sec\theta \int_{h_t}^h \alpha(h) + \sigma(h) dh\right)}{V_0 \cos\xi + \omega h} dh \right] \quad (3.30)$$

Note that the first term in this expression is invariant with respect to beam path while the second term contains such path dependent variables as wind, wind due to slew, and extinction coefficients. The first term is evaluated by this subroutine and the remainder evaluated later in the program inside the sbcct angle iteration loop by subroutine AV.

Standard values used for  $n_0 - 1$ ,  $p_0$ , and  $\gamma$  are  $2.72 \times 10^4$ ,  $1.01 \times 10^5 \text{ J/m}^3$ , and 1.4, respectively. A phase screen,  $\Phi(i,j)$ , is constructed by iteration of the intensity integral. Note that program performs this integration over a half plane of the aperture defined by  $-b < y < b$  and  $0 < x < b$  where  $b$  is the aperture diameter. The results are adjusted later in subroutine PHVAR for this method.

TABLE XIII  
FRTPHS Program Variables and Definitions

<u>Variable</u>	<u>Fortran</u>	<u>Name</u>	<u>Definition</u>
	<u>SUB</u>	<u>MAIN</u>	
$k \text{ (}\pi\text{)}^{-1}$	CK	-	$2\pi/\lambda$
$n_0 - 1$	const.	-	Refractive index term ( $2.72 \times 10^4$ )
$\gamma$	const.	-	Ratio of specific heats (1.4)
$p_0$	const.	-	Atmos. pressure ( $1.01 \times 10^5$ ) $\text{N/m}^2$
$\phi(x,y)$	PH(i,j)	PH(i,j)	Thermal blooming phase array

#### 15. FESPHS and COEFFFS

Once the phase screen has been constructed by subroutine FRTPHS, subroutine FESPFS removes the near, tilt, and focus curvature. The result is the phase aberration due to thermal blooming alone. Zernike polynomials are utilized for expressing these phase distortions with subroutine COEFFFS providing the required coefficients. These polynomials are



$$Z_0(x,y) = a_0 \quad (\text{mean}) \quad (3.31)$$

$$Z_1(x,y) = a_1 x \quad (x \text{ tilt}) \quad (3.32)$$

$$Z_2(x,y) = a_2 y \quad (y \text{ tilt}) \quad (3.33)$$

$$Z_3(x,y) = a_3 (x^2+y^2) + a_4 \quad (\text{focus}) \quad (3.34)$$

The expansion coefficients are given below and are computed relative to a uniform aperture weighting function  $W(x,y)$ .  $W(x,y) = 1$  inside the aperture and zero elsewhere. The integrals have been multiplied by 2 to compensate for the half plane integration of subroutine PHRPHS.

$$f_0 = 2a_0 \int \phi(x,y) W(x,y) dx dy \quad (3.35)$$

$$f_1 = 2a_1 \int \phi(x,y) W(x,y) x dx dy \quad (3.36)$$

$$f_2 = 2a_2 \int \phi(x,y) W(x,y) y dx dy \quad (3.37)$$

$$f_3 = 2 \int (a_3 (x^2+y^2) + a_4) \phi(x,y) W(x,y) dx dy \quad (3.38)$$

The final phase correction is given by

$$\begin{aligned} \phi(x,y) = & \phi(x,y) - f_1 Z_1(x,y) - f_2 Z_2(x,y) - f_3 Z_3(x,y) \\ & - f_0 Z_0(x,y) \end{aligned} \quad (3.39)$$

For a discussion of least squares fitting of Zernike polynomials, see [Ref. 36].



## 16. PHVAR

The phase variance due to thermal blooming is computed by this subcutine using the residual phase screen provided by RESPHS. Normalized with respect to the aperture field, the variance is given by

$$\sigma^2 = \frac{U(x,y) \phi^2(x,y) + U(x,y) \phi(x,y)}{U(x,y)} \quad (3.40)$$

TABLE XIV

PHVAR, RESPHS, and CCEFS Program Variable Definitions

<u>Variable</u>	<u>Fortran</u>	<u>Name</u>	<u>Definition</u>
	<u>SUB</u>	<u>MAIN</u>	
$\phi(x,y)$	PH(i,j)	PH(i,j)	Phase array
	SIGSQ0	SIGSQ0	Phase variance
$a_0 - a_4$	A1- A4	-	Zernike coeffs.
$f_0 - f_3$	PHMEAN	-	The expansion
	PHTITX	-	coefficients
	PHTITY	-	relative to a
	PHFCCUS	-	uniform weighting
			function

## 17. AV

AV evaluates the path dependent part (second term) of the thermal blooming equation 3.30 . (see section PRTPHS)  $\alpha(h)$  and  $\sigma(h)$  are the absorption coefficient and scattering coefficient, respectively.  $V_0$  is the user specified wind and  $\omega$  is the slew rate. The denominator represents the total transverse wind component across the beam.  $\theta$  is the zenith angle

and  $\xi$  is the angle of attack of  $V_0$  with respect to the beam.  $V_0$  has been assumed to be opposite in direction and parallel to the target to transmitter LCS slew motion. Note also that  $V_0$  will be applied as a constant the entire length of the beam path. This is discussed in chapter one.

TABLE XV  
AV Program Variables and Definitions

<u>Variance</u>	<u>Fortran</u>	<u>Name</u>	<u>Definition</u>
<u>SUB</u>		<u>Main</u>	
$\alpha(h) + \sigma(h)$	ALP	-	Total extinction coefficient
$\alpha(h) \text{ (km)}^{-1}$	ALS	-	Absorption coeff.
$\sec(\theta)$	SECCMG	SECCMG	secant of zenith angle
$V_0 \text{ (m/sec)}$	VO	VO	Wind
	PHILCT	PHILCT	Slew rate
$h_{\text{atm}}$ (meters)	HATMC	HATMC	Height of the atmosphere
$h_t$ (meters)	HT	HTRANS	Height of the transmitter

#### 18. ELCCM

The purpose of BLOOM is to provide reasonable results for thermal blooming degradation when the Irel values are below approximately 0.3. In this region, the exponential Strehl relation predicts unacceptably severe results. Therefore, when the phase variance is greater than 1.2, ELCCM computes an Irel value based on GUTSMTF results. GUTSMTF is a full wave optics propagation code using FFTs.

Curve fit polynomials were developed using GUTSMIF results for both a uniform and a truncated Gaussian aperture distribution. The resulting polynomials are

$$I_{rel} = \frac{1}{-.08705 + 2.9148\sigma + .1723\sigma^2} \quad (3.41)$$

$$I_{rel} = \frac{1}{1.2877 - 2.6491\sigma + 4.09603\sigma^2} \quad (3.42)$$

If the profile under consideration is a truncated Gaussian, i.e. the aperture diameter greater than the waist diameter of the beam, then the routine uses the truncated Gaussian polynomial. Otherwise, a combination of the two are used,

$$I_{rel_{tb}} = \left[1 - (d/b)^2\right] I_{rel_u} + (d/b)^2 I_{rel_{tg}} \quad (3.43)$$

where  $d$  is the aperture diameter and  $b$  is the waist diameter of the beam. [Ref. 37]

TABLE XVI  
EIOOM Program Variables and Definitions

<u>Variable</u>	<u>Fortran</u> <u>Sub</u>	<u>Name</u> <u>Main</u>	<u>Definition</u>
$\sigma^2$	S	SIGSQ	Phase variance
Irel <sub>tb</sub>	T	TBIOCM	Total blooming produced Irel
Irel <sub>u</sub>	TRU	-	Curve fit Irel for uniform aperture dist.
Irel <sub>tg</sub>	TRG	-	Curve fit Irel for Gaussian aperture dist.

#### 19. MTFATM

MTFATM computes the atmospheric MTF and if specified, applies a tilt due to turbulence correction. The MTF is given by

$$M_t(\bar{\rho}) = \exp \left[ -(\bar{\rho}/D)^{5/3} \left[ 1 - d(\bar{\rho}/D)^{1/3} \right] (D/\rho_0)^{5/3} \right] \quad (3.44)$$

where  $D$  is the aperture diameter,  $\rho_0$  is the coherence diameter and  $d$  is defined as  $1 - \text{ADAP}$ . ADAP is the fractional residual tilt due to turbulence and is a user specified parameter. If  $\text{ADAP} = 0$ ,  $M$  will represent the fully turbulence tilt corrected MTF. If  $\text{ADAP} = 1$ ,  $M$  will be the uncorrected MTF and may be written as

$$M_t(\bar{\rho}) = \exp \left[ -(\bar{\rho}/\rho_0)^{5/3} \right] \quad (3.45)$$

ADAP may be any value between 0 and 1.

TABLE XVII  
MIFATM Program Variables and Definitions

<u>Variable</u>	<u>Fortran</u> <u>Sub</u>	<u>Name</u> <u>Main</u>	<u>Definition</u>
$M_t(\bar{\rho})$	F	F3	Atmospheric MTF
$\rho_0$ (meters)	RHO	RHO	Coherence dia.
D (meters)	D	DIA	Aperture dia.

## 20. TRREFEL

TRREFEL computes the approximate Irel for a tilt corrected system. This value is used for comparison with the Irel produced by a perfect adaptive optics compensated system. The purpose of this comparison is to determine if noise will degrade the AO system to an extent as to make a full AC system undesirable. If this is the case, the program will apply tilt correction only to the beam.

## 21. FNDRHO

Subroutine FNDRHO calculates the coherence diameter that would result in the Irel value achieved by a perfect AO system. This is done by successive calls to subroutine TRBREI and iterating  $\rho_0$ . This new  $\rho_0$  then becomes a factor in the AC compensation. Specifically it will be used by subroutine MTFATM to produce the atmospheric MTF of the AC corrected system.

TABLE XVIII

TERRFL and FNDRHC Program Variables and Definitions

<u>Variable</u>	<u>Fortran Name</u>		<u>Definition</u>
	<u>Sub</u>	<u>Main</u>	
$M_t(\bar{\rho})$	F2	-	Atmospheric MTF
$M_a(\bar{\rho})$	F1	IFRMTF	Aperture MTF
Irel	EXD	EXD	Irel of perfect AO system

22. TITISO

The call to TITISO is made when adaptive optics have not been user specified and isoplanatic calculations have not been inhibited. Also, if the signal to noise ratio at the AO sensor is such that the AO system will provide tilt correction only, TITISC is called, again, provided isoplanatic calculations have not been inhibited.

The purpose of TITISC is to include beam wander due to isoplanatism. The 2-sigma-p tilt is computed and combined with the jitter 2-sigma-p. This combined term is then used to compute the jitter MTF.

23. FEITOT

FEITOT simply averages the relative intensities due to a multiplicative and an RSS (root sum squared) approach to combining thermal blooming and the other propagation effects.

$$Irel = \frac{Irel_{rss} + Irel_m}{2} \quad (3.46)$$

$Irel_m$  is the result of the multiplicative approach

$$Irel_m = Irel_{tb} * Irel_o \quad (3.47)$$

where  $Irel_{tb}$  is the Irel due to thermal blooming and  $Irel_o$  is the Irel due to beam quality, jitter, turbulence, isoplanatism and adaptive optics effects. The RSS approach is given by

$$Irel_{rss} = \left[ 1 + \left( \frac{1}{Irel_o} - 1 \right) + \left( \frac{1}{Irel_{tb}} - 1 \right) \right]^{-1} \quad (3.48)$$

TABLE XIX  
RELTOT Program Variables and Definitions

<u>Variable</u>	<u>Fortran</u>	<u>Name</u>	<u>Definition</u>
	<u>Sub</u>	<u>Main</u>	
$Irel_t$	T	TOTAL	Total Irel
$Irel_{rss}$	TR	TRSS	Irel by RSS method
$Irel_m$	TM	TMULT	Irel by multiplicative method
	EXD	EXD	Irel of perfect AO system
$Irel_o$	-	TTRUE	Irel due to all other effects
$Irel_{tb}$	-	TELCCM	Irel due to thermal blooming



## 24. ISOPLA

This routine calculates the MTF that characterizes the isoplanatic effect on the predictive or "look-ahead" adaptive optics system. The look-ahead angle is the major input parameter to this routine. The Fortran code was written by D.L. Fried [Ref. 38]. Fried develops the isoplanatic dependency of the AO system in terms of the effective antenna gain of the laser transmitter. The MTF that Fried formulates is given by

$$M_{\text{iso}}(\bar{\rho}) = \int_0^{\pi} 144.88 \lambda^{-2} \bar{\rho}^{-5/3} \cdot \sec(\theta) \cdot \mu(v \sec(\theta/\bar{\rho}), \phi) d\phi \quad (3.49)$$

where

$$x = v \sec(\theta/\bar{\rho}) \quad (3.50)$$

and

$$\begin{aligned} \mu(x, \phi) = \int_0^2 C_n^2 \left\{ 1 + (xh) - \frac{1}{2} \left[ 1 + 2(xh) \cos \phi + (xh)^2 \right]^{5/6} \right. \\ \left. - \frac{1}{2} \left[ 1 - 2(xh) \cos \phi + (xh)^2 \right]^{5/6} \right\} dh \end{aligned} \quad (3.51)$$

$\theta$  is the zenith angle and  $v$  is the target lead angle.

For detailed discussion of the theory and explicit development of the Fortran code, see [Ref. 39].



25. J0

J0 computes the zero order Bessel function based on the input argument. This routine is called by FARFLD in the calculation of the far-field irradiance.

# APPENDIX A

## GUTSAVG INPUT FILE

INPUT DATA FILE:

LASER:           CO CW EDL           5P(9) TRANSITION           4.99210 MICRONS  
 CLIMATE:        MIL-LATITUDE SUMMER, CLEAR DAY  
 CASE:           1

DIA	TELESCOPE DIAMETER	METERS	0.150000E+01
DIAOES	CENTRAL OBSCURATION DIAMETER	METERS	0.150000E+00
BEAMSZ	GAUSSIAN WAIST TEFU TELESCOPE	METERS	0.100000E+02
WAVE	CAVITY WAVELENGTH	METERS	0.499210E-05
PTOTAL	APERTURE TOTAL POWER	WATTS	0.200000E+07
THSEE	TURBULENCE SEEING	ARC-SEC	0.0
HGBNL	HEIGHT CF GROUND ABOVE MSL	METERS	0.300000E+03
TDFLMT	TIMES DIFFRACTION LIMITED	-	0.120000E+01
WAVEEC	RF WAVES DISTORTION	-	0.0
SCALEC	FEASE CORRELATION LENGTH	METERS	0.300000E+00
HTRANS	TRANSMITTER HEIGHT ABOVE MSL	METERS	0.300000E+03
HSAT	SATELLITE ALTITUDE	METERS	0.100000E+07
THETMX	MAXIMUM ZENITH ANGLE	DEGREES	0.300000E+02
LOFF	FLIGHT PATH OFFSET	METERS	0.0
RHO0	YURA'S TURB. COEFFICIENT LIA	METERS	0.0
VO	WIND VELOCITY	M/SEC	0.600000E+01
SIGJIT	Z-SIGMA-P JITTER	RADIANS	0.500000E-05
ADAP	FEAC. RESID. TURF. TILT	-	0.100000E+01
AOBICM	ELCCMING CORRECTION (0-1)	-	0.100000E+01
AVGSET	SFCT AVERAGING FACTOR (0-1)	-	0.100000E+01
NFLAGC	INCLUDE CLOUDS MODEL	-	0
NPLAGA	USE FULL ZONAL A-C SYSTEM	-	0
NOISC	INHIBIT ISOPLANATIC CALCS	-	1
ABSLCZ	ZENITH TRANS FOR A-C SENSOF	-	0.750000E+00
XJT	TARGET RADIANT INTENSITY	W/STER	0.250000E+03
BWIDTH	A-C SYSTEM BANDWIDTH	HERTZ	0.500000E+03
NA	NUMBER CF A-C SYSTEM ACTUATORS		0.102400E+04
N1	NUMBER CF ANGLE INTERVALS		30
N2	DESCRIPTION INTEGRATION INTERVALS		200
N3	TURBULENCE INTEGRATION INTERVALS		100
N4	MIE INTEGRATION INTERVALS		200
N5	THERMAL BLOOMING INTEGRATION INTERVALS		100

# APPENDIX B

## GUTSAVG OUTPUT FILE

LASEE:	CC CW ED1	5P(9) TRANSITION	4.99210 MICRONS
CLIMATE:	MID-LATITUDE SUMMER, CLEAR DAY		
CASE:	1		
DIA	TELESCOPE DIAMETER	METERS	.150E+01
DIAORS	CENTRAL OBSCURATION DIAMETER	METERS	.150E+00
EFAMSZ	GAUSSIAN WAIST THRU TELESCOPE	METERS	.100E+02
WAVE	CAVITY WAVELENGTH	METERS	.499210E-05
PTOTAL	APERTURE TOTAL POWER	WATTS	.200E+07
THSEE	TURBULENCE SEEING	ARC-SEC	.000E+00
HGRN1	HEIGHT OF GROUND ABOVE MSL	METERS	.300E+03
TDPLMT	TIMES DIFFRACTICA LIMITED	-	.120E+01
WAVEEC	RMS WAVES DISTORTION	-	.000E+00
SCALEC	PHASE CORRELATION LENGTH	METERS	.300E+00
HTRANS	TRANSMITTER HEIGHT ABOVE MSI	METERS	.300E+03
HSAT	SATELLITE ALTITUDE	METERS	.100E+07
THEIMX	MAXIMUM ZENITH ANGLE	DEGREES	.300E+02
LCFF	FLIGHT PALE OFFSET	METERS	.000E+00
BHOO	YURA'S TURE. COHERENCE DIA	METERS	.000E+00
VO	WIND VELOCITY	M/SEC	.060E+02
SIGJIT	2-SIGMA-P JITTER	RADIANS	.500E-05
ALAF	FRAC. RESIL. TURE. TILT	-	.100E+01
AOBLCM	BLOCKING COEFFICIENT (0-1)	-	.100E+01
AVGSFT	SPOT AVERAGING FACTOR (0-1)	-	.100E+01
NFLAGA	USE FULL ZENAI A-C SYSTEM	-	0
NOISC	INHIBIT ISCELANATIC CALCS	-	1
ABSLC2	ZENITH TRANS FOR A-O SENSE	-	.750E+00
XJT	TARGET RADIANT INTENSITY	W/STEB	.250E+03
BWIDTB	A-O SYSTEM BANDWIDTH	HERTZ	.500E+03
NA	NUMBER OF A-C SYSTEM ACTUATORS		1024.
N1	NUMBER OF ANGLE INTERVALS		30
N2	ABSORPTION INTEGRATION INTERVALS		200
N3	TURBULENCE INTEGRATION INTERVALS		100
N4	MTF INTEGRATION INTERVALS		200
N5	THERMAL BLOCKING INTEGRATION INTERVALS		100

PATH ANALYSIS RESULTS:

STEP NO.	RANGE (KM)	SLEW (MRAD/SEC)	CMEGA (LEG)	TIME (SEC)	ATMOS. TRANSMISSION SCAT	ABSCRIP	RHO (CM)
1.	999.738	7.1582	1.08	2.63	0.99802	0.53314	51.1
2.	1000.045	7.1541	2.16	5.27	0.99802	0.53302	51.0
3.	1000.659	7.1459	3.24	7.90	0.99802	0.53278	51.0
4.	1001.579	7.1337	4.31	10.53	0.99802	0.53242	51.0
5.	1002.805	7.1175	5.39	13.16	0.99801	0.53195	50.9
6.	1004.334	7.0973	6.46	15.80	0.99801	0.53135	50.9
7.	1006.167	7.0732	7.52	18.43	0.99800	0.53064	50.8
8.	1008.301	7.0453	8.59	21.06	0.99800	0.52982	50.8
9.	1010.735	7.0138	9.65	23.70	0.99799	0.52888	50.7
10.	1013.465	6.9786	10.70	26.33	0.99799	0.52782	50.6
11.	1016.490	6.9400	11.74	28.96	0.99798	0.52665	50.5
12.	1019.806	6.8981	12.79	31.59	0.99797	0.52537	50.4
13.	1023.413	6.8530	13.82	34.23	0.99796	0.52398	50.2
14.	1027.305	6.8048	14.85	36.86	0.99796	0.52248	50.1
15.	1031.481	6.7537	15.86	39.49	0.99795	0.52088	50.0
16.	1035.935	6.6999	16.87	42.13	0.99794	0.51917	49.8
17.	1040.666	6.6435	17.88	44.76	0.99792	0.51735	49.6
18.	1045.668	6.5847	18.87	47.39	0.99791	0.51544	49.5
19.	1050.939	6.5237	19.85	50.02	0.99790	0.51342	49.3
20.	1056.474	6.4606	20.83	52.66	0.99789	0.51130	49.1
21.	1062.269	6.3955	21.79	55.29	0.99787	0.50909	48.9
22.	1068.319	6.3288	22.75	57.92	0.99786	0.50679	48.7
23.	1074.621	6.2604	23.69	60.56	0.99785	0.50439	48.5
24.	1081.169	6.1907	24.63	63.19	0.99783	0.50191	48.3
25.	1087.959	6.1196	25.55	65.82	0.99781	0.49933	48.1
26.	1094.988	6.0475	26.46	68.45	0.99780	0.49668	47.9
27.	1102.250	5.9744	27.36	71.09	0.99778	0.49393	47.7
28.	1109.740	5.9006	28.25	73.72	0.99776	0.49111	47.4
29.	1117.455	5.8260	29.13	76.35	0.99774	0.48821	47.2
30.	1125.388	5.7510	30.00	78.99	0.99772	0.48524	47.0

## TRANSMISSION ANALYSIS OUTPUT:

STEP	TRANSMISSION COEFFICIENTS DUE TO AMF LOSS THERMAL SPREADING WITH AO FICCMING	RANGE SCALE	MAX IRRAD (KW/CM2)	FLUENCE (KJ/CM2)
1.	0.11826 1.00000 0.01522	0.9999	0.5779E-04	C.1522E-03
2.	0.11824 1.00000 0.01521	0.9993	0.5770E-04	C.3041E-03
3.	0.11821 1.00000 0.01518	0.9981	0.5753E-04	C.4555E-03
4.	0.11817 1.00000 0.01515	0.9963	0.5726E-04	C.6063E-03
5.	0.11810 1.00000 0.01511	0.9938	0.5692E-04	C.7562E-03
6.	0.11802 1.00000 0.01505	0.9908	0.5649E-04	C.9049E-03
7.	0.11793 1.00000 0.01499	0.9872	0.5597E-04	C.1052E-02
8.	0.11782 1.00000 0.01491	0.9830	0.5539E-04	C.1198E-02
9.	0.11770 1.00000 0.01483	0.9783	0.5472E-04	C.1342E-02
10.	0.11756 1.00000 0.01473	0.9730	0.5399E-04	C.1484E-02
11.	0.11740 1.00000 0.01463	0.9672	0.5320E-04	C.1624E-02
12.	0.11724 1.00000 0.01452	0.9610	0.5234E-04	C.1762E-02
13.	0.11705 1.00000 0.01440	0.9542	0.5142E-04	C.1898E-02
14.	0.11686 1.00000 0.01427	0.9470	0.5046E-04	C.2030E-02
15.	0.11664 1.00000 0.01414	0.9393	0.4945E-04	C.2161E-02
16.	0.11642 1.00000 0.01400	0.9313	0.4839E-04	C.2288E-02
17.	0.11618 1.00000 0.01385	0.9228	0.4730E-04	C.2413E-02
18.	0.11593 1.00000 0.01369	0.9140	0.4618E-04	C.2534E-02
19.	0.11566 1.00000 0.01354	0.9049	0.4504E-04	C.2653E-02
20.	0.11538 1.00000 0.01337	0.8954	0.4387E-04	C.2768E-02
21.	0.11509 1.00000 0.01320	0.8857	0.4268E-04	C.2881E-02
22.	0.11479 1.00000 0.01303	0.8757	0.4148E-04	C.2990E-02
23.	0.11448 1.00000 0.01286	0.8654	0.4028E-04	C.3096E-02
24.	0.11415 1.00000 0.01268	0.8550	0.3907E-04	C.3199E-02
25.	0.11381 1.00000 0.01250	0.8443	0.3786E-04	C.3298E-02
26.	0.11346 1.00000 0.01232	0.8335	0.3665E-04	C.3395E-02
27.	0.11310 1.00000 0.01213	0.8226	0.3545E-04	C.3488E-02
28.	0.11273 1.00000 0.01195	0.8115	0.3427E-04	C.3578E-02
29.	0.11235 1.00000 0.01176	0.8003	0.3309E-04	C.3666E-02
30.	0.11196 1.00000 0.01158	0.7891	0.3193E-04	C.3750E-02

CASE DATA AND CALCULATED FACTORS:

TRANSMITTER DIAMETER = 150.00 CM  
 CAVITY WAVELENGTH = 4.992100 UM  
 APERTURE TICAL POWER = 2.0000 MW  
 TIMES DIFFRACTION LIMIT = 1.20  
 (WIDE ANGLE SCATTERING)  
 TRANSMITTER ALTITUDE = 300.00 M  
 SATELLITE ALTITUDE = 1000.00 KM  
 MAX ZENITH ANGLE = 30.00 DEG  
 FLIGHT PATH OFFSET = 0.0 KM  
 RHOO = 0.5105E+02 CM  
 WIND VELOCITY = 6.00 M/SEC  
 HEIGHT OF GROUND = 300.00 M  
 OPT SEEING AT 5500A = 0.15E+01 ARC-SEC

BLCOMING ADAPTIVE OPTICS FACTOR = 0.1000E+01  
 IRRADIANCE AREA AVERAGING FACTOR = 0.1000E+01

TELESCOPE DIMENSIONS:  
 OUTER DIAMETER = 150.00 CM  
 INNER DIAMETER = 15.00 CM  
 GAUSSIAN WAIST DIAMETER = 1000.00 CM

RMS WAVES DISTORTION = 0.1031E+00  
 PHASE CORRELATION LENGTH = 0.3000E+02 CM

FOR THE FULL ZONAL A-C MODEL:  
 ZENITH TRANS. AT A-C SENSOR = 0.7500E+00  
 TARGET RADIANT INTENSITY = 0.2500E+03 W/STER  
 ADAPTIVE OPTICS BANDWIDTH = 0.5000E+03 HERTZ  
 NUMBER OF ACTUATORS = 1024.

THIS RUN -  
 IS THE BASIC CCDE WITH ONLY SOME MEASURE OF TILT CORRECTION  
 AND WITHOUT AN ISOPLANATIC MODEL

NUMBER OF INTERVAL STEPS FOR:  
 ANGULAR INTERVAL = 30  
 ABSORPTION INTEGRATION = 200  
 RHC CALCULATION = 100  
 MTF CALCULATION = 200  
 THERMAL ELCCING = 100

ZENITH LCG AMPLITUDE VARIANCE = 0.4905E-02  
 RELATIVE IRRADIANCE REDUCTION = 0.9951E+00

ZENITH LOCK-AHEAD ANGLE = 0.5227E+02 URAD

ISOPLANATIC JITTER (2-SIGMA-P) = 0.2004E+07

2-SIGMA-P BEAM JITTER = 5.00 URAD  
 TURBULENCE JITTER REJECTION = 0.1000E+01  
 (RESIDUAL = INITIAL \* ADAP)

===== PROPAGATION RESULTS =====  
 INTEGRATED FLUX ON TARGET = 0.007499 KJ/CM2  
 TOTAL ILLUMINATION TIME = 157.97 SEC

# APPENDIX C

## GUTSAVG PROGRAM LISTING

```

C *****
C GUTSAVG      NAVAL POSTGRADUATE SCHOOL VERSION 1.2
C MODIFICATION 1.2
C LATEST CHANGE DATE 22 FEB 84
C THIS VERSION OF GUTSAVG HAS BEEN MODIFIED FOR IBM 370/360
C COMPATABILITY. VARIABLE NAME LENGTHS HAVE BEEN CHANGED AND
C APPROPRIATE FORTRAN CHANGES MADE. MACHINE GENERATED ERRORS MAY
C STILL OCCUR DUE TO UNRESOLVED CDC/IBM DIFFERENCES
C THE CLOUD MODEL HAS BEEN REMOVED FROM THIS VERSION
C *****
C ===== MEMCFY ALLOCATION AND VARIABLE ASSIGNMENTS =====C
C
C   REAL BOMTF(300)
C   REAL JITEMF(300)
C   REAL A(100,14)
C   REAL B(15)
C   REAL PH(101,201)
C   REAL TISC(300)
C   REAL LOFF,MU
C   REAL IRRMIF(300)
C   REAL LY,IZ
C   REAL NASCET,NU,ISCANG,ISOANO,NA
C
C   INTEGER TITLE1(80),TITLE2(80),TITLE3(80)
C   INTEGER DESCR(40,80)
C
C   COMMON /ATMO/ EATMO
C   COMMON /EQ/ TIFLMT,VARBQ,WAVEBQ,SCALEQ
C   COMMON /ARBPLE/ CIA,CIAOBS,EEAMSZ,UO
C
C ===== CONSTANTS ASSIGNMENTS =====C
C
C   ML=201
C   JJ=0
C   TSTOLD=0.
C   F4=1
C   PI=2.*ARCSIN(1.)
C   MLH=ML/2+1
C   EATMO=3.F4
C   TAU=0.
C   XMW=1.E+6
C   XCM=1.E+2
C   XKW=1.E-3
C   XK2=1.E-7
C   BTD=90./ARCSIN(1.)
C   REARTH=6.4E6
C   MU=3.986E14
C   THETSP=2.*PI/(24.*3600.)
C   VSURF=REARTH*1EE15P
C
C   CALL ERRSET (208,256,-1,1,1)
C
C ===== DATA INPUT SECTOR =====C
C
C   READ (5,530) (TITLE1(I),I=1,80)
C   READ (5,530) (TITLE2(I),I=1,80)
C   READ (5,530) (TITLE3(I),I=1,80)
C
C   READ (5,510) (DESCR(1,II),II=1,50), CIA
C   READ (5,510) (DESCR(2,II),II=1,50), DIACBS
C   READ (5,510) (DESCR(3,II),II=1,50), EEAMSZ
C   READ (5,510) (DESCR(4,II),II=1,50), WAVE
C   READ (5,510) (DESCR(5,II),II=1,50), FTCTIAL
C   READ (5,510) (DESCR(6,II),II=1,50), THSEB
C   READ (5,510) (DESCR(7,II),II=1,50), EGRND
C
C -----
C (EITHER TIFLMT OR WAVEBQ MUST BE DEFINED, BUT NOT BOTH)

```



```

C-----
C
READ (5,510) (DESCR(8,II),II=1,50), TDFLMT
READ (5,510) (DESCR(9,II),II=1,50), WAVEBQ
READ (5,510) (DESCR(10,II),II=1,50), SCALBQ
READ (5,510) (DESCR(11,II),II=1,50), HTRANS
READ (5,510) (DESCR(12,II),II=1,50), HSAT
READ (5,510) (DESCR(13,II),II=1,50), THETMX
READ (5,510) (DESCR(14,II),II=1,50), LOFF
READ (5,510) (DESCR(15,II),II=1,50), RHCO
READ (5,510) (DESCR(16,II),II=1,50), VO
READ (5,510) (DESCR(17,II),II=1,50), SIGJIT
READ (5,510) (DESCR(18,II),II=1,50), ADAP
READ (5,510) (DESCR(19,II),II=1,50), ACBLOM
READ (5,510) (DESCR(20,II),II=1,50), AVGSFT
READ (5,520) (DESCR(21,II),II=1,50), NFLAGA
READ (5,520) (DESCR(22,II),II=1,50), NCISO

```

```

C-----
C
IF FULL AC CORRECTION IS NOT USED, THE following
PARAMETERS ARE NOT REALLY USED. ONLY BWIDTH
HAS AN EFFECT, it CAUSES the LOCK AHEAD ANGLE TO
BE LARGER BY TAU*PHILOT.

```

```

C-----
C
READ (5,510) (DESCR(23,II),II=1,50), ABSLOZ
READ (5,510) (DESCR(24,II),II=1,50), XJT
READ (5,510) (DESCR(25,II),II=1,50), BWIDTH
READ (5,510) (DESCR(26,II),II=1,50), NA

```

```

C-----
C
ITERATION LOOP LIMITS:
N1 NUMBER OF SUBTEETHA INTERVALS FROM 0 TO THETMX
N2 NUMBER OF INTEGRATION INTERVALS FOR ABSORPTION
N3 NUMBER OF INTEGRATION INTERVALS FOR TURBULENCE
N4 NUMBER OF INTEGRATION INTERVALS FOR MTF
N5 NUMBER OF SUBINTERVALS USED FOR SLANT PATH UPDATE FOR
THERMAL FLOWING

```

```

C-----
C
READ (5,520) (DESCR(27,II),II=1,50), N1
READ (5,520) (DESCR(28,II),II=1,50), N2
READ (5,520) (DESCR(29,II),II=1,50), N3
READ (5,520) (DESCR(30,II),II=1,50), N4
READ (5,520) (DESCR(31,II),II=1,50), N5

```

```

C===== ECHO CHECK OUTPUT SECTOR =====C

```

```

C
WRITE (6,190)
WRITE (6,195) (TITLE1(I),I=1,80)
WRITE (6,195) (TITLE2(I),I=1,80)
WRITE (6,195) (TITLE3(I),I=1,80)
WRITE (6,180) (DESCR(1,II),II=1,50), CIA
WRITE (6,180) (DESCR(2,II),II=1,50), DIAOBS
WRITE (6,180) (DESCR(3,II),II=1,50), BEAMSZ
WRITE (6,180) (DESCR(4,II),II=1,50), WAVE
WRITE (6,180) (DESCR(5,II),II=1,50), PTOTAL
WRITE (6,180) (DESCR(6,II),II=1,50), THSEE
WRITE (6,180) (DESCR(7,II),II=1,50), HGEN
WRITE (6,180) (DESCR(8,II),II=1,50), TDFLMT
WRITE (6,180) (DESCR(9,II),II=1,50), WAVEBQ
WRITE (6,180) (DESCR(10,II),II=1,50), SCALBQ
WRITE (6,180) (DESCR(11,II),II=1,50), HTRANS
WRITE (6,180) (DESCR(12,II),II=1,50), HSAT
WRITE (6,180) (DESCR(13,II),II=1,50), THETMX
WRITE (6,180) (DESCR(14,II),II=1,50), LOFF
WRITE (6,180) (DESCR(15,II),II=1,50), RHCO
WRITE (6,180) (DESCR(16,II),II=1,50), VO
WRITE (6,180) (DESCR(17,II),II=1,50), SIGJIT
WRITE (6,180) (DESCR(18,II),II=1,50), ADAP
WRITE (6,180) (DESCR(19,II),II=1,50), ACBLOM
WRITE (6,180) (DESCR(20,II),II=1,50), AVGSFT
WRITE (6,185) (DESCR(21,II),II=1,50), NFLAGA
WRITE (6,185) (DESCR(22,II),II=1,50), NCISO
WRITE (6,180) (DESCR(23,II),II=1,50), ABSLOZ
WRITE (6,180) (DESCR(24,II),II=1,50), XJT

```



```

WRITE (6,180) (DESCR(25,II),II=1,50), BWIDTH
WRITE (6,180) (DESCR(26,II),II=1,50), NA
WRITE (6,185) (DESCR(27,II),II=1,50), N1
WRITE (6,185) (DESCR(28,II),II=1,50), N2
WRITE (6,185) (DESCR(29,II),II=1,50), N3
WRITE (6,185) (DESCR(30,II),II=1,50), N4
WRITE (6,185) (DESCR(31,II),II=1,50), N5

C===== DATA REALIGNMENT SECTOR =====C
C
IF (SCALBQ.EQ.0.) SCALBQ=DIA/5.
IF (WAVEEQ.NE.0.) WAVEBQ=(2.*PI*WAVEBQ)**2
SGJTO=SIGJIT
IF (NFLAGA.EQ.1) ALAP=0.
IF (NOISC.EQ.1) ISCAN0=1.E10
NASORT=SCBT(NA)
LOGABS=-ALOG(AESLCZ)
TAU=1./BWIDTH/PI

C===== INITIAL CALCULATIONS SECTOR =====C
C
IF (RHOO.EQ.0.AND.THSEE.NE.0.) RHOO=(WAVE/.55E-6)**1.2*(.054/THSEE
1)
THETMX=THETMX/FID
HSAID=HSAT-HTRANS
HAEVGD=HTBANS-EGEND
IF (HABVGD.LT.C.) HAEVGD=0.

C
R=REARTH+HTRANS
RS=REARTH+HSAT
NFIGSN=0

C-----
C COMPUTE EARTH CENTER ANGLE OFF-SET
C-----
C
ANGOFF=LCFF/R
A2=ANGOFF/2.

C-----
C COMPUTE COORDINATE TRANSLATIONS DUE TO CFF-SET
C-----
C
LY=+2.*R*SIN(A2)*COS(A2)
LZ=2.*R*SIN(A2)**2

C-----
C COMPUTE EARTH CENTER ANGULAR RATE
C-----
C
THETDT=SQRT(MU/RS**3)

C-----
C COMPUTE ORBITAL SPEED
C-----
C
VSAT=THETDT*RS

C-----
C ADJUST INSTANTANEOUS SLEWRATE FOR ROTATION OF EARTH,
C assuming both are collinear.
C-----
C
THETDT=AES(THETLT-THETSF)

C-----
C COMPUTE VELOCITY OF SATELLITE RELATIVE TO THE TRANSMITTER SITE
C-----
C
VS=THETDT*RS

C-----
C COMPUTE INITIAL LIMITS ON THE TIME AND ANGLE EARTH CENTER
C for an or line flight path
C-----
C

```

```

ECANG=ARCOS(R*SIN(THETMX)/RS)+THETMX-PI/2.
TIMEX2=ECANG/THETCT
TIMTOT=2.*TIMEX2
DTIME=TIMEX2/N1

```

```

C-----
C IF SATELLITE ALTITUDE IS AN THE ORDER OF THE RADIUS OF
C THE earth, gtsif (fcotprint) WORKS BETTER BY SETTING
C the time step instead of the angle step
C-----

```

```

C IF (HSAT.GT.BEABTE/2.) DTIME=10.

```

```

C-----
C COMPUTE VACUUM IRRADIANCE AND APERTURE MTF. NOTE THAT THE
C POINT SPACING HERE MUST BE THE SAME AS USED IN THE MTF
C INTEGRATION BELOW. HENCE WE DEFINE DX NOW.
C-----

```

```

C DX=DIA/N4

```

```

C-----
C THE CALL TO UOCST DETERMINES THE CONSTANT THAT MAKES THE EXIT
C APERTURE POWER FCTAL.
C-----

```

```

C CALL UOCST (PICTAL,M1)
C CALL PARFID (DX,1ISC,IRRMTF,M1,N4,HSATD,WAVE,PTOTAL,PMAXO)

```

```

C-----
C IF THE WAVEBQ IS NOT SPECIFIED AS INPUT, COMPUTE ON BASIS OF
C TDFLMT.
C-----

```

```

C IF (WAVEEQ.EQ.C.) CALL DETWAV (IRRMTF,DX,N4)

```

```

C-----
C IF TDFLMT WAS NOT SPECIFIED, COMPUTE IT .
C-----

```

```

C IF (TDFLMT.NE.C.) GO TO 10
C CALL BQIEEL (IRRMTF,N4,DX,TBQ)
C TDFLMT=SQRT(1./TEQ)
C CONTINUE

```

```

C-----
C DEFINE BEAM QUALITY MTF ARRAY.
C-----

```

```

C CALL BM (EQMTF,DX,N4)

```

```

C-----
C DEFINE JITTER MTF ARRAY.
C-----

```

```

C CALL JIT (JITMTF,DX,N4,SGJITC,WAVE)

```

```

C-----
C COMPUTE ZENITH ABSORPTION, SCATTERING, AND RHOO VALUES.
C-----

```

```

C CALL ABSCEB (N2,HTRANS,TABSO)
C CALL SCAT (N2,HTRANS,ISCATO)
C IF (RHOO.EQ.0.) CALL RHOTRB (N3,HTRANS,HABVGD,WAVE,RHOO)

```

```

C-----
C DEFINE SEEING AT 5500A
C-----

```

```

C THSEE=(WAVE/.55E-6)**1.2*(.054/RHOO)

```

```

C IF (NPLAGA.GE.1.AND.NOISO.EQ.C) CALL ISCTRB (N3,HTRANS,HABVGD,WAVE
C 1,ISOANO)

```

```

C-----
C CALCULATE LOG AMPLITUDE SCINTILLATION FOR ZENITH ANGLE.
C-----

```

```

C-----
C
C      CALL SCINT (SIGY2,N3,HTRANS,HGFND,WAVE)
C-----
C      COMPUTE THE THERMAL BLOOMING PHASE DISTORTION THAT does not depend
C      SLANT PATH CHARACTERISTICS
C-----
C      CALL PRTPHS (M1,MLH,WAVE,PH)
C      CALL RESPHS (M1,MLH,PH)
C      CALL PHVAR (M1,MLH,PTOTAL,PH,SIGSQ0)
C-----
C      INITIALIZE ACCUMULATED FLUENCE TO ZERO
C-----
C      FLUX=0.
C-----
C      SET SNR FLAG TO CFF
C-----
C      NFIGSN=0
C-----
C***** M A I N      P R O G R A M      L C O P *****C
C-----
C      LCOP ON IRRADIANCES AND ACCUMULATED FLUENCES FOR A FIXED LOFF
C-----
C      DO 120 I=1,N1
C-----
C      COMPUTE TOTAL LENGTH OF ILLUMINATION TIME FROM (+,-)
C      OVER PASS ANGLE
C      THIS IS THE TOTAL TIME. WE USE HALF OF THIS TO DETERMINE THE
C      FUNCTION EVALUATION ANGLE.
C-----
C      TIME=2.*((I-1)*TIMEF+DIME/2.)
C-----
C      COMPUTE EARTH CENTER ANGLE AT CN LINE COORDINATES AND TIME/2.
C      THIS ANGLE IS TO THE MID-POINT OF THE INTEGRATION INTERVAL.
C      THE ANGLE ECANGF, COMPUTED LATER, IS TO THE UPPER LIMIT OF THE
C      integration limit.
C***** THE COMMENTED ECANG SHOULD BE USED WHEN IT IS DESIRED THAT
C      THE INTEGRATION SHOULD START AT THE LOW POINT AND INCREASE
C      TOWARDS THE ZENITH. THE CURRENT CALCULATION STARTS AT
C      THE ZENITH AND GOES DOWN.
C-----
C*** ECANG=(TIME-TIMEF)/2.*TIMEFDT
C      ECANG=TIME/2.*TIMEFDT
C-----
C      COMPUTE TARGET COORDINATES
C-----
C      X0=RS*SIN(ECANG)
C      Z0=RS*COS(ECANG)
C      X=X0
C      Y=LY*COS(ANGOFF)+(Z0-R+LZ)*SIN(ANGOFF)
C      Z=-LY*SIN(ANGOFF)+(Z0-R+LZ)*COS(ANGOFF)
C-----
C      COMPUTE CN LINE OF SIGHT ANGLE OF SAT.
C      THIS ANGLE IS NOT USED AT PRESENT. IT IS THE ANGLE OF THE
C      SAT AS MEASURED FROM A POINT UNDER THE GROUND TRACK.
C-----
C      THETA=ATAN(RS*SIN(ECANG)/(RS*COS(ECANG)-R))

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C-----
C COMPUTE RANGE TO TARGET
C-----
C RANGE=SQRT(X**2+Y**2+Z**2)
C-----
C INSTANTANEOUS SLEW RATE
C-----
C VY=VS*COS(ECANG)
C VY=-VS*SIN(ECANG)*SIN(ANGCFF)
C VZ=-VS*SIN(ECANG)*CCS(ANGCFF)
C WX=Y*VZ-Z*VY
C WY=Z*VX-X*VZ
C WZ=X*VY-Y*VX
C PHIDOT=SQRT(WX**2+WY**2+WZ**2)/RANGE**2
C-----
C COMPUTE ANGLE FROM ZENITH
C-----
C OMEGA EQUALS ANGLE DOWN FROM ZENITH
C OMWIND EQUALS ANGLE OF WIND ATTACK TO LCS IF TARGET
C MOTION AND WIND ARE COPLANAR.
C-----
C OMEGA=ARCCS(Z/RANGE)
C OMWIND=ARCSIN(X/RANGE)
C-----
C COSOMG=CCS(OMEGA)
C SECOMG=1./COSOMG
C CCSWIND=CCS(OMWIND)
C-----
C ADJUST FOR SLANT PATH, BLOOMING LOSS, ABERRATION LOSS, SCATTERING
C LOSS, AND TURBULENCE RHO
C-----
C CALL AV (NS,VC,PHIDOT,HTRANS,CCSWIND,cosomg,E)
C SIGSQ=SIGSQ0*E
C-----
C APPLY THERMAL BLOOMING
C ADAPTIVE OPTICS DEGREE OF COMPENSATION
C-----
C SIGSQ=SIGSQ*ACEICM
C-----
C SIG=SQRT(SIGSQ)
C TBLOOM=EXP(-SIGSQ)
C IF (SIGSQ.GT.1.2) CALL BLOOM (CIA,BEAMSZ,SIGSQ,TBLOOM)
C TAES=TABS0**SECCMG
C TSCAT=TSCAT0**SECCMG
C RHC=RH00*COSCMG**(.6)
C-----
C COMPUTE LOOK AHEAD ANGLE ASSUMING EARTH ROTATION AND SATELLITE MOTION
C ARE IN THE SAME DIRECTION.
C-----
C TWCT=RANGE*2./3.EE
C DRT=TWCT*(ABS(VSA1-VSURF))
C PECJAN=ARCCOS(X/RANGE)
C PECJ=DRT*SIN(PECJAN)
C NU=PROJ/RANGE+TAU*PHIDOT
C IF (I.EQ.1) ZENU=NU
C-----
C IF executed, the following is a full ao simulation
C-----
C IF (NFLAGA.EQ.C) GC TC 40

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C-----
C MCDIFY BEC FCB EFFECT OF ADAPTIVE OPTICS
C-----
C RHCID=RHC
C RHO=RHO
C RO=2.1*RHO
C-----
C DETERMINE APPROXIMATE I-REL TO SEE IF AC SHOULD BE USED,
C given PRESENT NOISE.
C-----
C DCE=DIA/RHO
C CALL TRBREL (IERMTF,DIA,N4,DX,EXDTST,RHC)
C-----
C COMPUTE RESIDUAL VARIANCE DUE TO PERFECT ADAPTIVE OPTICS,
C INFINITE BANDWIDTH, AND FINITE NUMBER OF ACTUATORS.
C-----
C D1=.320*(DIA/RO/NASQET)**(1.6667)
C TES=LOGAES*SECCMG
C TSNSR=EXP(-TES)
C-----
C DETERMINE PHASE VARIANCE ASSOCIATED WITH SENSOR.
C-----
C PHSERR=8.5E-6*BWIDTH*NA**2*(RANGE/5.E5*2.5/DIA)**4*(80./XJT*.5/TSE
C INSE)**2
C-----
C INCREASE RESIDUAL PHASE VARIANCE AND COMPUTE THE I-REL.
C-----
C D1=D1+PHSERR
C-----
C COMPUTE I-REL OF AC TURBULENCE CORRECTED BEAM.
C-----
C EXD=EXP(-D1)
C-----
C IF AO CORRECTED I-REL IS LESS THAN NO AC CORRECTION, ASSUME
C ONLY TILT CORRECTION IS USED.
C-----
C IF (EXD.LT.EXDTST.OR.NFLGSN.EQ.1) GO TO 20
C CALL PNDEBO (EXD,RHC,DIA,RHO,DX,N4,IRRMTF)
C GO TO 30
C 20 CONTINUE
C-----
C THIS SETS A FLAG TO PRINT THAT AO SYSTEM IS ONLY TILT
C-----
C RHC=RHOLD
C NFLGSN=1
C 30 CONTINUE
C-----
C ESTABLISH TEST INCREMENTS TO SEE IF FULL ISOPLANATIC CALCULATION
C NEEDS TO BE DONE.
C-----
C COMPUTE THE ISOPLANATIC ANGLE.
C-----
C ISCANG=CCSOMG**(2.6667)*ISOANO
C TSINEW=NC/ISCANG
C TSTDIF=AES(TSINEW**1.666667-TSTOLD)

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C      EISDIP=EXP(TSTIDIP)
C      IF (NISO.EQ.1) TSTOLD=TSTNEW**1.666667
C-----
C      DETERMINE IF ISOPLANATIC MTF SHOULD BE RE-COMPUTED
C-----
C      NISO=0
C      IF (ETSDIF.GT.1.1) NISO=1
C      IF (I.EQ.1) NISO=1
C      IF (NOISC.EQ.1) NISO=0
40     CONTINUE
C-----
C      REDUCE PEAK IRRADIANCE BY SLANT DISTANCE
C-----
C      TMAXSC=(ESATL/RANGE)**2
C-----
C      THIS ALLOWS ONE TO INCLUDE TILT ISOPLANATISM. NOTE HOWEVER, THAT
C      IF THE FULL ADAPTIVE OPTICS ALGORITHM IS USED WITH THE ISOPLANATISM
C      CORRECTION, THEN THIS CALL SHOULD NOT BE USED-REPEAT-SHOULD NOT BE
C      USED. ALSO NOTE THAT A VERTICAL TURBULENCE PROFILE IS NEEDED
C      WHEN EVER THIS ROUTINE IS USED.
C-----
C      IF (NFLGSN.EQ.1.AND.NOISO.EQ.0) GO TO 50
C      IF (NOISC.EQ.1.CE.NFLAGA.EQ.1) GO TO 60
50     CONTINUE
C      CMX=NU
C      CMY=0.
C      CALL TLTISO (DIA,CMX,CMY,BESTLT,SECOMG,HTRANS,HABVGD)
C
C      SIGJIT=SQRT(SGJITC**2+RESILT)
60     CONTINUE
C-----
C      COMPUTE IRRADIANCE DECREASE DUE TO AMPLITUDE SCINTILLATION FOR THE
C      OFF ZENITH PASS. NOTE THAT THIS AS LOSS WILL ONLY BE APPLIED IF
C      FULL ADAPTIVE OPTICS COMPENSATION IS ASSUMED.
C-----
C      CALL SINTLS (IAMP,SIGXZ,SECOMG)
C-----
C      CALCULATE EFFECTS OF JITTER AND TURBULENCE
C-----
C      SUM=0.
C      DX2=DX/2.
C-----
C      IT IS IMPORTANT TO NOTE THAT ALL THE ARRAYS ARE DEFINED
C      TO BEGIN AT DX/2.
C-----
C      X=DX2
C      DO 110 J=1,N4
C      IF (X.GT.DIA) GO TO 100
C      F1=IRRMTF(J)
C      CALL MTFATM (X,DIA,BHO,ADAP,F2)
C      F3=JITMTF(J)
C      IF (NFLAGA.EQ.1.AND.NFLGSN.EQ.0) GO TO 70
C      IF (NOISC.EQ.0) CALL MTFJIT (X,SIGJIT,WAVE,F3)
70     CONTINUE
C      F4=1.
C      IF (NFLAGA.EQ.0.CE.NCISO.EQ.1.CE.NFLGSN.EQ.1) GO TO 90
C      F4=TIISO(J)
C      IF (NISO.EQ.1) CALL ISOPLA (JJ,NU,X,SECOMG,WAVE,F4,HTRANS,HABVGD,T
110    ISC,N4,J)
C      CONTINUE
C      F5=BQMTF(J)
C      SUM=SUM+F1*F2*F3*F4*F5*X
90     CONTINUE
100    X=X+DX

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110  CCNINUE
      TTURB=SUM*2.*FI*DX
C-----
C      CALCULATE THE RESULTING INSTANTANEOUS INTENSITY
C-----
C      CONVERT TO AN APPROACH WHICH AVERAGES THE RESULT OF AN RSS
C      TREATMENT OF THERMAL BLOOMING WITH A MULTIPLICATIVE TREATMENT
C-----
      SSCT=1./TTURB-1.
      SSCB=1./TELOCM-1.
      SSC=SSCT+SSCB
      TMULT=TTURB*TEICCM
      TRSS=1./(1.+SSC)
      CALL RELTCT (TTCAL, TRSS, TMULT)
      PMAX=PMAXO*TAES*TSCAT*TMAXSC*TTCAL
C-----
C      APPLY AVERAGEING FACTOR
C      APPROPRIATE TO SPC1 SIZE DESIRED
C-----
      PMAX=PMAX*AVGSET
C-----
C      IF FULL AO IS USED, DECREASE IRRADIANCE FOR AMPLITUDE
C      SCINTILLATION EFFECTS
C-----
      TAMPL=1.0
      IF (NFLAGA.EQ.1.AND.NFLGSN.EQ.0) TAMPL=TAMP
      IF (TAMPL.LT.0.5) TAMPL=0.5
      PMAX=PMAX*TAMPL
C-----
C      ACCUMULATED FLUX
C-----
      FLUX=FLUX+PMAX*DTIME
C-----
C      COMPUTE INTEGRATED TIMES AND ACCUMULATED ANGLES. THE IRRADIANCE
C      FUNCTION HAS BEEN EVALUATED AT INTERVAL MID-POINTS.
C-----
      ECANGF=(TIME+DTIME)/2.*THETDT
      XOF=RS*SIN(ECANGF)
      ZOF=RS*CCS(ECANGF)
      XF=XOF
      YF=LY*COS(ANGOFF)+(ZOF-R+LZ)*SIN(ANGCFF)
      ZF=-LY*SIN(ANGCFF)+(ZOF-R+LZ)*CCS(ANGOFF)
      RANGEF=SQRT(XF**2+YF**2+ZF**2)
C-----
      OMEGAF=ARCOS(ZF/RANGEF)
C-----
C      TIME OF ILLUMINATION FROM ZENITH TO THETA. THIS IS ALSO
C      EVALUATED AT THE LOWER LIMIT AND NOT THE MID-POINT.
C      IF THE COMPUTATIONS ARE DONE FROM THE THETX TO ZENITH INSTEAD
C      OF THE WAY THEY ARE, THE TIME DEFINITION NEEDS TO BE CHANGED.
C-----
      TILLUM=TIME/2.+DTIME/2.
C===== LOOP RESULTS STORAGE SECTOR =====C
      A(I,1)=I
      A(I,2)=RANGE*KKW
      A(I,3)=PERIOD/KKW
      A(I,4)=OMEGAF*BTG
      A(I,5)=TILLUM
      A(I,6)=TSCAT
      A(I,7)=TAES
      A(I,8)=REC*XCM

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A(I,9)=T10RB
A(I,10)=TAMPL
A(I,11)=TELOCM
A(I,12)=TMAXSC
A(I,13)=FMAX*XK2
A(I,14)=FLUX*XK2
120 CONTINUE
C===== FINAL RESULTS OUTPUT SECTOR =====C
C
B(1)=DIA*XCM
B(2)=WAVE*XMW
B(3)=PICTAL/XMW
B(4)=TDFIMT
B(5)=HTRANS
B(6)=HSAT*XKW
B(7)=THETIM*RTL
B(8)=LOFF*XKW
B(9)=RHO0*XCM
B(10)=VO
B(11)=HGFEND
B(12)=THSEE
C
WRITE (6,220)
WRITE (6,240) ((A(I,J),J=1,8),I=1,N1)
WRITE (6,230)
WRITE (6,250) (A(I,1),A(I,J),J=9,14),I=1,N1)
WRITE (6,330) (B(11),LL=1,12)
WRITE (6,130) ACBICM,AVGSPT
C
DIA=DIA*XCM
DIAOBS=DIAOBS*XCM
BEAMSZ=BEAMSZ*XCM
WRITE (6,140) DIA,DIAOBS,BEAMSZ
C
SCALBQ=SCALBQ*XCM
WRITE (6,150) WAVEBQ,SCALBQ
B(1)=ABSICZ
B(2)=XJT
B(3)=BWILTH
B(4)=NA
WRITE (6,380) (B(11),LL=1,4)
WRITE (6,260)
IF (NFLAGA.EQ.0.AND.NOISO.EQ.1) WRITE (6,310)
IF (NFLAGA.EQ.1.AND.NOISO.EQ.0) WRITE (6,280)
IF (NFLAGA.EQ.1.AND.NOISO.EQ.1) WRITE (6,290)
IF (NFLAGA.EQ.0.AND.NOISO.EQ.0) WRITE (6,300)
WRITE (6,340) N1,N2,N3,N4,N5
C
ESIGXZ=EXP(-SIGXZ)
WRITE (6,160) SIGXZ,ESIGXZ
C
ZENNU=ZENNU*XMF
WRITE (6,320) ZENNU
C
RESLT=SQRT(RESLT)*XMW
WRITE (6,360) RESLT
C
SGJITO=SGJITO*XMW
WRITE (6,350) SGJITC,ADAP
C
FLUX=FLUX*XK2*2.
TILLUM=TILLUM*2.
WRITE (6,370) FLUX,TILLUM
IF (NFLAGSN.EQ.1) WRITE (6,170)
SIOP
C===== I/O FORMAT STATEMENTS =====C
S000 FORMAT (50X,F20.0)
S100 FORMAT (50A1,F20.0)
S200 FORMAT (50A1,I20)
S300 FORMAT (50A1)
1300 FORMAT (10X,'BLCCING ADAPTIVE OPTICS FACTOR = ',E10.4,/,

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140 | FCFRMT (1CX, 'IRRADIANCE AREA AVERAGING FACTOR = ', E10.4, '/')
| FCFRMT (1CX, 'TELESCOPE DIMENSICNS:', '/',
| 1CX, 'OUTER DIAMETER = ', F10.2, ' CM', '/')
| 1CX, 'INNER DIAMETER = ', F10.2, ' CM', '/')
| 1CX, 'GAUSSIAN WAIST DIAMETER = ', F10.2, ' CM', '/')
150 | FCFRMT (1CX, 'RMS WAVES DISTORTION = ', E10.4, '/')
| 1CX, 'PHASE CORRELATION LENGTH = ', E10.4, ' CM', '/')
160 | FCFRMT (1CX, 'ZENITH LOG AMPLITUDE VARIANCE = ', E12.4, '/', 10X, 'SEIA',
| 'TIVE IRRADIANCE REDUCTION = ', E12.4, '/')
170 | FCFRMT (1CX, 'NOTE=====THE ADAPTIVE OPTICS SYSTEM USED WILL ',
| 'PROVIDE DEGRADED PERFCRMANCE OVER THE TILT ONLY CASE', '/')
180 | FCFRMT (1CX, 5CA1, E20.6)
185 | FCFRMT (1CX, 5CA1, 120)
190 | FCFRMT (1H1, 9X, 'INPUT DATA FILE:', '/')
195 | FCFRMT (1CX, 80A1, '/')
220 | FCFRMT (1H1, 9X, 'PATH ANALYSIS RESULTS:', '/',
| 6X, 'STIFF', 10X, 'RANGE', 9X, 'SLEW', 6X, 'OMEGA', 7X, 'TIME',
| 5X, 'ATMCS', 'TRANSMISSION', 10X, 'RHC', '/',
| 7X, 'NO.', 11X, ' (KM)', 5X, 'MRAD/SEC', 4X, ' (DEG)',
| 6X, ' (SEC)', 8X, 'SCAT', 6X, 'ABSORP', 9X, ' (CM)', '/')
230 | FCFRMT (1E1, 9X, 'TRANSMISSION ANALYSIS CUPUL:', '/',
| 16X, 'TRANSMISSION COEFFICIENTS', 13X, 'RANGE', 5X, 'MAX IRRAD',
| 11X, 'FLUENCE', '/',
| 4X, 'STEEP', 5X, 'DUE IO', 5X, 'AMP LCSS', 4X,
| 'THERMAL', 4X, 'SCALE', 5X, ' (KW/CM2)', 5X,
| ' (KJ/CM2)', '/', 10X, 'SPREADING', 6X, 'WITH AO', 5X, 'BLOOMING', '/')
240 | FCFRMT (7X, F3.C, 5X, F10.3, 5X, F8.4, 5X, F6.2, 5X, F6.2, 5X,
| F7.5, 5X, F7.5, 5X, F8.1, 5X, F10.5, 5X, F10.5, 5X, F10.4, 5X, E10.4,
250 | FCFRMT (7X, F3.C, 5X, F10.5, 5X, F10.5, 5X, F10.4, 5X, E10.4,
| 5X, E10.4, '/')
260 | FCFRMT (1CX, 'THIS RUN -')
270 | FCFRMT (12X, 'INCLUDES THE STATISTICAL CLOUD MODEL')
280 | FCFRMT (12X, 'INCLUDES THE FULL ZONAL AC MODEL WITH AN ',
| 'ISOPLANATISM MODEL')
290 | FCFRMT (12X, 'INCLUDES THE FULL ZONAL AC MODEL WITHOUT AN ',
| 'ISOPLANATISM MODEL')
300 | FCFRMT (12X, 'INCLUDES FULL TILT CORRECTION WITH TILT ',
| 'ISOPLANATISM')
310 | FCFRMT (12X, 'IS THE BASIC CODE WITH ONLY SOME MEASURE OF ',
| 'TILT CORRECTION', '/', 12X, 'AND WITHOUT AN ISOPLANATIC',
| 'MODEL', '/')
320 | FCFRMT (1CX, 'ZENITH LOOK-AHEAD ANGLE = ', E10.4, ' URAD', '/')
330 | FCFRMT (1H1, 9X, 'CASE DATA AND CALCULATED FACTORS:', '/',
| 1CX, 'TRANSMITTER DIAMETER = ', F10.2, ' CM', '/')
| 1CX, 'CAVITY WAVELENGTH = ', F10.6, ' UM', '/')
| 1CX, 'APERTURE TOTAL POWER = ', F10.4, ' MW', '/')
| 1CX, 'TIMES DIFFRACTION LIMIT = ', F10.2, '/',
| 1CX, ' (WIDE ANGLE SCATTERING)', '/',
| 1CX, 'TRANSMITTER ALTITUDE = ', F10.2, ' M', '/')
| 1CX, 'SATELLITE ALTITUDE = ', F10.2, ' KM', '/')
| 1CX, 'MAX ZENITH ANGLE = ', F10.2, ' DEG', '/',
| 1CX, 'FLIGHT PATH OFFSET = ', F10.2, ' KM', '/')
| 1CX, 'RHC = ', E10.4, ' CM', '/')
| 1CX, 'WIND VELOCITY = ', F10.2, ' M/SEC', '/',
| 1CX, 'HEIGHT OF GROUND = ', F10.2, ' M', '/')
| 1CX, 'OPT SEEING AT 5500A = ', E10.2, ' ARC-SEC', '/')
340 | FCFRMT (1CX, 'NUMBER OF INTERVAL STEPS FOR:', '/',
| 12X, 'ANGULAR INTERVAL = ', I10, '/',
| 12X, 'ABSCPTION INTEGRATION = ', I10, '/',
| 12X, 'RHC CALCULATION = ', I10, '/',
| 12X, 'MTF CALCULATION = ', I10, '/',
| 12X, 'THERMAL BLOOMING = ', I10, '/')
350 | FCFRMT (1CX, '2-SIGMA-F BEAM JITTER = ', F10.2, ' URAD', '/',
| 1CX, 'TURBULENCE JITTER REJECTION = ', E10.4, '/',
| 1CX, 'RESIDUAL = INITIAL * ADAP', '/')
360 | FCFRMT (1CX, 'ISPLANATIC JITTER (2-SIGMA-P) = ', E10.4, '/')
370 | FCFRMT (1CX, '===== PROPAGATION RESULTS =====', '/',
| 1CX, 'INTEGRATED FLUX ON TARGET = ', F15.6, ' KJ/CM2', '/',
| 1CX, 'TOTAL ILLUMINATION TIME = ', F15.2, ' SEC')
380 | FCFRMT (1CX, 'FOR THE FULL ZONAL A-O MODEL:', '/',
| 12X, 'ZENITH TRANS. AT A-O SENSOR = ', E10.4, ' W/STER', '/',
| 12X, 'TARGET RADIANT INTENSITY = ', E10.4, ' W/STER', '/',
| 12X, 'ADAPTIVE OPTICS BANDWIDTH = ', E10.4, ' HERTZ', '/',
| 12X, 'NUMBER OF ACTUATORS = ', F10.0, '/')
END

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SUBROUTINE ALFA (A,Z)
C----- CALCULATE THE TOTAL MOLECULAR ABSORPTION
C
DIMENSION ALT(20),ATA(20)
C***** THIS DATA FOR CO 5P9 FROM AFWL INFO, REPORTEDLY BASED ON AN
C***** UPDATE OF THE MCCLATCHY LINE DATA. THE WAVELENGTH FOR THIS
C***** TRANSITION IS 4.99210 MICRONS.
C***** ATMOSPHERE IS MID-LATITUDE SUMMER, CLEAR DAY.
1 DATA ALT/0.0,1.0,2.0,3.0,4.0,5.0,6.0,7.0,8.0,9.0,10.0,12.0,14.0,
DATA ATA/0.356,0.269,0.148,7.28E-02,3.35E-02,1.51E-02,6.88E-03,
1 3.40E-03,1.61E-03,1.79E-03,3.46E-04,6.50E-04,1.78E-05,
2 1.06E-05,6.21E-06,3.61E-06,0.0,0.0,0.0,0.0/
NI=19
INDX=1
A=C.
IF ((Z*3.279).GE.1.E5) RETURN
H=2*1.E-3
C----- SEARCH FOR THE ALTITUDE INDEX
C
DO 10 I=1,NL
IF (H.LT.ALT(I)) GO TO 10
INDX=I
CONTINUE
10 R=(H-ALT(INDX))/(ALT(INDX+1)-ALT(INDX))
A=R*(ATA(INDX+1)-ATA(INDX))+ATA(INDX)
A=A/1000.
RETURN
END

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C      SUBROUTINE ALPS (S,Z)
C----- CALCULATE THE TOTAL SCATTERING
C      DIMENSION ALT(20),ATS(20)
C***** THIS DATA FOR CO SP9 FROM AFWL INPO, REPORTEDLY BASED ON AN
C***** UPDATE OF THE MCCLATCHY LINE DATA. THE WAVELENGTH FOR THIS
C***** TRANSITION IS 4.99210 MICRONS.
C***** ATMOSPHERE IS MIC-LATITUDE SUMMER, CLEAR DAY.
C      DATA ALT/0.0,1.0,2.0,3.0,4.0,5.0,6.0,7.0,8.0,9.0,10.0,12.0,14.0,
1      DATA ATS/1.41E-03,1.36E-04,1.09E-04,5.57E-05,4.54E-05,3.50E-05,
1      DATA ATS/2.60E-05,1.79E-05,1.14E-05,4.39E-05,3.64E-05,2.91E-05,
2      DATA ATS/2.62E-05,2.66E-05,2.41E-05,1.89E-05,7.00E-06,1.06E-05,
3      DATA ATS/3.28E-06,1.61E-06/
      NI=19
      S=0.
      IF ((Z*3.279) .GE. 1.E5) RETURN
      H=Z*1.E-3
      INDX=1
C----- SEARCH FOR THE ALTITUDE INDEX
C      DO 10 I=1,NL
      IF (H.LT.ALT(I)) GO TO 10
      INDX=I
      CONTINUE
10     R=(H-ALT(INDX))/(ALT(INDX+1)-ALT(INDX))
      S=H*(ATS(INDX+1)-ATS(INDX))+ATS(INDX)
      S=S/1000.
      RETURN
      END

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SUBROUTINE ABSCEB (N,HT,T)
C----- CALCULATES ZENITH THE TOTAL INTEGRATED MOLECULAR TRANSMISSION
C
COMMON /AIMO/ HAIMO
DEIH=(HAIMO-HT)/N
HEIGHT=HT+DELE/2.
ALPZ=0.
DO 10 I=1,N
CALL ALFA (ALP,HEIGHT)
ALPZ=ALPZ+ALP
HEIGHT=HEIGHT+DELE
10 CONTINUE
ALPZ=ALPZ*DELE
T=EXP(-ALPZ)
RETURN
END

```

```

C      SUBROUTINE SCAT (A,HT,T)
C----- CALCULATES ZENITH THE TOTAL INTEGRATED SCATTERED TRANSMISSION
C
COMMON /ATMO/ HATMC
DELH=(HATMO-HT)/N
HEIGHT=HT+DELH/2.
ALPS=0.
DO 10 I=1,N
CALL ALPS (ALS,HEIGHT)
ALPS=ALPS+ALS
HEIGHT=HEIGHT+DELH
CONTINUE
ALPS=ALPS*DELH
T=EXP(-ALPS)
RETURN
END
10

```

```

SUBROUTINE BRCTFE (N,HT,HG,W,RFC)
C----- COMPUTES YUHAS ZENITH ATMOSPHERIC COHERENCE DIAMETER
C
COMMON /ATMO/ RATIO
TPI=4.*ASIN(1.)
CK=TPI/W
CKSQ=CK*CK
DELB=(HAIMO-HT)/FICAT(N)
HEIGHT=HG+DELB/2.
SUM=0.
DO 10 I=1,N
CALL CN2E (HEIGHT,CN2)
SUM=SUM+CN2
HEIGHT=HEIGHT+DELB
CONTINUE
10 CN1=SUM*DELB
DEN=2.91*CKSQ*CN1
RHC=(6.88/DEN)**(.6)
RFC=RHO/2.-1
RETURN
END

```

```

C      SUBROUTINE FARFIE (DX2,F,G,M1,N4,HSATD,WAVE,PTOTAL,PMAXO)
C----- COMPUTES THE FARFIELD IRRADIANCE OF THE APERTURE DISTRIBUTION
C----- AND THEN COMPUTES THE CORRESPONDING APERTURE MTF
C
      DIMENSION F(M1),G(M1)
      COMMON /ARBFIE/ LIA,LIACES,BEAMSZ,UO
      PI2=ARCSIN(1.)
      PI=2.*PI2
      TWOPI=2.*PI
      CK=TWOPI/WAVE
      CKR=CK/HSATD
      LIASQ=LIA**2
      DOBSQ=LIAOBS**2
      RFCCUS=1.2*HSATD*WAVE/SQRT(LIASQ-DOBSQ)
      FACTOR=4.
      FACTOR=2.5
      FACTOR=5.
      RLIM=FACTOR*RFCCUS
      DX0=(LIA-LIAOBS)/2./ML
      DX1=RLIM/ML
      R1=DX1/2.
      DO 20 I=1,ML
      SUM=0.
      R0=LIAOBS/2.+DX0/2.
      DO 10 J=1,ML
      Z=CKR*R0*F1
      CALL JO (Z,A)
      CALL FIEI (R0,UR)
      SUM=SUM+A*UR*F0
      R0=R0+DX0
      BY DIVIDING BY FICTAL, THE MTF WILL BE UNITY AT THE ORIGIN.
      F(I)=(SUM*CKR*DX0)**2/PTOTAL
      R1=R1+DX1
C----- COMPUTE FMAXO ON AXIS
C
      SUM=0.
      R0=LIAOBS/2.+DX0/2.
      DO 30 I=1,ML
      CALL FIEI (R0,UR)
      SUM=SUM+UR*R0
      R0=R0+DX0
      PMAXO=(SUM*CKR*DX0)**2
C----- CNORM- FIXES THE MTF SO THAT THE MTF INTEGRATION PRODUCES AN
C----- IDEAL VALUE.
C
      CNORM=(WAVE*HSATD)**2*PMAXO/FICTAL
C----- COMPUTE THE MTF
C
      R2=DX2/2.
      DO 50 I=1,N4
      SUM=0.
      R1=DX1/2.
      DO 40 J=1,ML
      Z=CKR*R1*F2
      CALL JO (Z,A)
      SUM=SUM+A*F(J)*R1
      R1=R1+DX1
      G(I)=SUM*TWOPI*DX1/CNORM
      R2=R2+DX2
      RETURN
      END

```





```

80  EP1=B
    B=Y*BP1-EP2+A5(I)
    P=.5*(E-EP2)
    B=0.0
    BP1=0.0
    DC 90 I=1,11
    EP2=BP1
90  EP1=B
    E=Y*BP1-EP2+A6(I)
    Q=4*(B-BF2)/AE
    B=SIGN(1.0,X)
    Y=AB-2.35619449019235
    F=.797884560802865*(F*COS(Y)-Q*SIN(Y))/SQRT(AB)
    F=B*P
    RETURN
    END

```

```

      SUBROUTINE FIELD (R,UR)
C----- COMPUTES EXIT APERATURE FIELD DISTRIBUTION.  NOTE IT MUST BE
C----- AXI-SYMETRIC.
C
      COMMON /ARBPLE/ LIA,LIAOBS,BEAMSZ,UO
      UR=0.
      D=2.*R
      IF (D.GT.DIA.CF.D.LI.LIAOBS) RETURN
      EBRAD=BEAMSZ/2.
      UR=UO*EXP(-(R/EBRAD)**2)
      RETURN
      END

```

```

SUBROUTINE UOCST (ET,N)
C----- COMPUTES NORMALIZATION CONSTANT GIVING TOTAL ENERGY IN BEAM
C
COMMON /ARBFL/ LIA,LIAOBS,BEASZ,UO
PI=2.*ASIN(1.)
BC=DIA/2.
BCSQ=RO**2
RI=DIAOBS/2.
RISQ=RI**2
DX=ROSQ/N
CST=PI*DX
Y=DX/2.
UO=1.
SUM=0.
DO 10 I=1,N
  RCOTX=SQRT(X)
  IF (RCOTX.GT.BC.CR.RCOTX.IT.RI) GO TO 10
  CALL FIELD (RCOTX,UR)
  SUM=SUM+UR**2
  Y=Y+DX
TEMP=SUM*CST
UO=SQRT(ET/TEMP)
RETURN
END
10

```

```

      SUBROUTINE MTFATM (X,D,RHO,ADAF,F)
C----- COMPUTES ATMOSPHERIC MTF FUNCTION
C
      XL=X/D
      A1=1.-ADAF
      DRHO=D/RHO
      F=EXP(-XL**(1.6667)*(1.-A1*XD**(.3333))*DRHO**(1.6667))
      RETURN
      END

```

```

C      SUBROUTINE MTFJIT (X,SIGJIT,WAVE,F)
C----- COMPUTES JITTER MTF FUNCTION
C
TPI=4.*AR SIN(1.)
CK=TPI/WAVE
F=EXP(-(CK*X*SIGJIT)**2/8.)
RETURN
END

```

```

SUBROUTINE MTFEQ (X,F)
C
C----- COMPUTES RANDCM PHASE MTF.  ASSUMES A GAUSSIAN CORRELATION
C----- FUNCTION.
C
COMMON /EQ/ TFLMT,VARBQ,WAVEEQ,SCALEQ
TEMP=1.-EXP(-(1/SCALEQ)**2)
F=EXP(-VARBQ*TEMP)
RETURN
END

```

10

```
SUBROUTINE BQIRE1 (A,N4,DX,REL)
DIMENSION A(N4)
SUM=0.
X=DX/2.
DO 10 I=1,N4
CALL MTPEC (X,F)
SUM=SUM+A(I)*F*X
X=X+DX
CONTINUE
REL=SUM*DX*6.2831852
RETURN
END
```

```

SUBROUTINE DETWAV (A,DX,N4)
C
C----- IF THE RMS WAVES OF PHASE DISTORTION ARE NOT SPECIFIED,
C----- THEN THIS ROUTINE WILL DETERMINE THE APPROPRIATE WAVEBQ THAT
C----- PRODUCES THE SPECIFIED TDFLMT.
C
COMMON /EC/ TDFLMT,VARBQ,WAVEBQ,SCALEC
DIMENSION A(N4)
RELO=1./TDFLMT**2
VAREQ=-ALCG(RELO)
DVEC=VAREC/10.
TEST=.005
NSIGN0=1.
10 CONTINUE
CALL BCIREL (A,N4,DX,REL)
DEEL=REL-RELO
IF (ABS(DEEL)/RELC.LT.TEST) GC TO 40
IF (DEEL.LT.0.) GC TO 20
NSIGN1=1
GC TO 30
20 NSIGN1=-1
30 CCNTINUE
IF (NSIGN1.NE.NSIGN0) DVBQ=DVEC/2.
VABBQ=VARBQ+DVEC*NSIGN1
NSIGN0=NSIGN1
GC TO 10
40 CONTINUE
TWOPI=6.2831852
WAVEBQ=SQRT(VABBQ)/TWOPI
RETURN
END

```



```

C      SUBROUTINE JIT (A,DX,N4,SIGJIT,WAVE)
C----- COMPUTES ARRAY FCF JITTER MTP.
C
      DIMENSION A(N4)
      X=DX/2.
      DO 10 I=1,N4
      CALL MTFJIT (X,SIGJIT,WAVE,F)
      A(I)=F
10     X=X+DX
      RETURN
      END

```

```

      SUBROUTINE BM (A,IX,N4)
C----- COMPUTES ARRAY FOR BEAM QUALITY MTF.
C
      DIMENSION A(N4)
      X=DX/2.
      DO 10 I=1,N4
      CALL MTFEC (X,F)
      A(I)=F
10    X=X+DX
      RETURN
      END

```

```

SUBROUTINE CN2H (HEIGHT,CN2)
C
C   CALCULATE ATMOSPHERIC VERTICAL TURBULENCE
C
C---- HUFNAGELS LATEST MODEL-GOOD ONLY ABOVE 3 KILOMETERS
C
CN2=2.2*(1.E-5*10.**(-.3)*HEIGHT)**10.*EXP(-HEIGHT/1000.)
CN2=CN2+.2E-16*EXP(-HEIGHT/1500.)
CN2=CN2*.7
C
C---- THIS MODIFICATION IS USED to include turbulence at lower alts
C
CN2=CN2+1.E-14*EXP(-HEIGHT/100.)
RETURN
END

```

```

SUBROUTINE AV (N,VO,PHIDCT,HT,CCSWND,COSOMJ,E)
C
C--- COMPUTES THAT PART OF THERMAL FLICKERING THAT CHANGES WITH SLANT PATH
C
COMMON /ATMO/ BATEC
COSSQ=CCSWND
DEIH=(HATMO-HT)/N
RG=DELH/2.
HEIGHT=HT+DELE/2.
VOCOS=VO*COSSQ
SUM=0.
SUMAS=0.
DO 10 I=1,N
CALL ALFA (ALA,HEIGHT)
CALL ALFS (ALS,HEIGHT)
SUMAS=SUMAS+ALS+ALA
ALCSS=EXP(-SUMAS*DELH/COSCHG)
SUM=SUM+ALCSS*ALA/(VOCOS+RG*PHIDCT)
RG=RG+DELE
HEIGHT=HEIGHT+DELH
10 CONTINUE
SUM=SUM*DELH
E=SUM**2
RETURN
END

```

```

SUBROUTINE PRTRHS (ML,MLH,WAVE,PH)
C----- COMPUTES THAT PART OF THERMAL BLOOMING PHASE THAT DOES NOT DEPEND
C----- ON SLANT RANGE
C
COMMON /ARBFLD/ DIA,DIAOES,BEAMSZ,UO
DIMENSION PH(MLH,ML)
MLM=ML-1
MLHM=MLH-1
DIASQ=DIA**2
RACSQ=DIASQ/4.
PI4=ARCSIN(1.)/2.
CK=8.*PI4/WAVE
SCALE=CK*(2.72E-4*.4)/(1.01E5*1.4)
RCSQ=(DIA/2.)**2
RISQ=(DIACBS/2.)**2
DEIN=DIA/MLM
XI=DEIN/2.
YI=-DIA/2.+DEIN/2.
X=XI
DO 20 I=1,MLHM
Y=YI
SUM=0.
XSQ=X*X
DO 10 J=1,MLM
RSQ=Y*Y+XSQ
R=SQRT(RSQ)
FACTOR=0.
IF (RSQ.LT.RCSQ.AND.FSQ.GT.RISQ) CALL FIELD (R,FACTOR)
FACTOR=FACTOR**2
SUM=SUM+FACTOR
PH(I,J)=SUM*SCALE*DEIN
Y=Y+DEIN
CONTINUE
X=X+DEIN
CONTINUE
RETURN
END
10
20

```

```

SUBROUTINE RESEHS (M1,MLH,PH)
C
C----- CALCULATES THE RESIDUAL PHASE AFTER THE MEAN,TILT, AND FOCUS
C----- HAVE BEEN REMOVED.
C
  DIMENSION PH(M1H,ML)
  COMMON /ARBFLC/ DIA,DIAOBS,PEAPSZ,UO
  MLHM=MLH-1
  MLM=ML-1
  DELN=DIA/MLM
  XI=DELN/2.
  YI=-DIA/2.+DELN/2.
  RSCQ=(DIA/2.)**2
  RISQ=(DIAOBS/2.)**2
C
C      COMPUTE NORMALIZATION CONSTANTS
C
  CALL COEFS (AC,A1,A2,A3,A4,MLM,MLHM,DELN)
C----- COMPUTE EXPANSION COEFFICIENTS
C
  SUM1=0.
  SUM2=0.
  SUM3=0.
  SUM4=0.
  X=XI
  DO 20 I=1,MLHM
    XSQ=X**2
    Y=YI
    DO 10 J=1,MLM
      YSQ=Y**2
      BSC=XSQ+YSQ
      IF (RSQ.GT.BSC.OR.RSQ.LT.RISQ) GO TO 10
      CALL FIELD (SQFI(BSC),UR)
C----- DETERMINE EXPANSION COEFFICIENTS RELATIVE TO A UNIFORM
C----- WEIGHTING FUNCTION.
C
    FT=0.
    IF (ABS(UR).GT.1.E-2) FT=1.
    FACTOR=PE(I,J)*FT
    SUM1=SUM1+FACTOR*X
    SUM2=SUM2+FACTOR*Y
    SUM3=SUM3+FACTOR*RSQ
    SUM4=SUM4+FACTOR
  10 Y=Y+DELN
  20 X=X+DELN
C----- ADJUST FOR HALF PLANE INTEGRATION
  SUM1=0.
  SUM2=SUM2*2.
  SUM3=SUM3*2.
  SUM4=SUM4*2.
C
  DELNSQ=DELN**2
  PHMEAN=AC*SUM4*DELNSQ
  PHILTIX=A1*SUM1*DELNSQ
  PHILTY=A2*SUM2*DELNSQ
  PHFOC=(A3*SUM3+A4*SUM4)*DELNSQ
C
C----- SUBTRACT THE MEAN,TILT,AND FOCUS CURVATURES.
C
  X=XI
  DO 40 I=1,MLHM
    XSQ=X**2
    Y=YI
    DO 30 J=1,MLM
      YSQ=Y**2
      BSC=XSQ+YSQ
      IF (RSQ.GT.BSC.OR.RSQ.LT.RISQ) GO TO 30
      PH(I,J)=PH(I,J)-PHILTIX*A1*X-PHILTY*A2*Y-PHFOC*(A3*RSQ+A4)-PHMEAN*A
  30 Y=Y+DELN
  40 X=X+DELN
  RETURN
  END

```

```

C      SUBROUTINE COEFS (A0,A1,A2,A3,A4,MLM,MLHM,DELN)
C----- COMPUTES TILT AND FOCUS NORMALIZATION CONSTANTS
C
COMMON /AREPLI/ DIA,DIAOES,BEAMSZ,UO
RQSQ=(DIA/2.)**2
RISQ=(DIAOES/2.)**2
DELNSQ=DELN**2
YI=-DIA/2.+DELN/2.
XI=DELN/2.
X=XI
SUM1=0.
SUM2=0.
SUM3=0.
SUM4=0.
DO 20 I=1,MLHM
XSC=X**2
Y=YI
DO 10 J=1,MLM
YSC=Y**2
ESQ=XSC+YSC
ESCSQ=ESQ**2
IF (RQSQ.GT.RSCQ.OB.RSQ.LT.RISQ) GO TO 10
CALL FIELD (SCFT(ESQ),UR)
C-----DETERMINE NORMALIZATION COEFFICIENTS RELATIVE TO A UNIFORM
C-----WEIGHTING FUNCTION.
C
FT=0.
IF (ABS(UR).GT.1.E-2) FT=1.
FACTOR=FT
SUM1=SUM1+FACTOR
SUM2=SUM2+FACTOR*YSC
SUM3=SUM3+FACTOR*YSC
SUM4=SUM4+FACTOR*ESCSQ
10 Y=Y+DELN
20 X=X+DELN
C----- ADJUST FOR HALF PLANE INTEGRATION
SUM1=SUM1*2.
SUM2=SUM2*2.
SUM3=SUM3*2.
SUM4=SUM4*2.
C
A0=SQRT (1./(SUM1*DELNSQ))
A1=SQRT (1./(SUM2*DELNSQ))
A2=SQRT (1./(SUM3*DELNSQ))
B=-SUM1/(SUM2+SUM3)
A3=SQRT (F*B/(F*B+SUM4-SUM1)*DELNSQ)
A4=A3/B
C
RETURN
END

```



```

C      SUBROUTINE PHVAR (M1,MLH,ETOTAL,PH,SIGSQ0)
C-----COMPUTES THE THERMAL BLOOMING PHASE VARIANCE
C-----VARIANCE IS COMPUTED LIKE THE STREHL RATIO ACCORDING TO THE
C-----FIELD AS A WEIGHTING FUNCTION.
C
COMMON /ARBFLD/ IIA, DIAOBS, BEAMSZ, UO
DIMENSION PH(MLH,ML)
RCSQ=(DIA/2.)**2
RISQ=(DIAOBS/2.)**2
MLM=ML-1
MLHM=MLH-1
DELN=DIA/MLM
XI=DELN/2.
YI=-DIA/2.+XI
X=XI
SUM1=0.
SUM2=0.
SUM3=0.
DO 30 I=1,MLHM
Y=YI
XSQ=X*X
DO 20 J=1,MLM
RSQ=XSQ+Y*Y
IF (RSQ.GT.RCSQ.CE.BSQ.LT.RISQ) GO TO 10
CALL FIELD (SQRT(RSQ),UR)
SUM1=SUM1+UR
SUM2=SUM2+UR*PH(I,J)**2
SUM3=SUM3+UR*PH(I,J)
10 CONTINUE
Y=Y+DELN
20 CONTINUE
X=X+DELN
30 CONTINUE
C-----ADJUST FOR HALF PLANE INTEGRATION
SUM1=SUM1+2.*DELN**2
SUM2=SUM2+2.*DELN**2
SUM3=SUM3+2.*DELN**2
C
C      NORMALIZE WITH RESPECT TO INTEGRAL OF THE FIELD.
C
SIGSQ0=SUM2/SUM1-(SUM3/SUM1)**2
C
RETURN
END

```

```

      SUBROUTINE ISC1EB (N,HT,HG,W,ISOANG)
C----- COMPUTE ZENITH ISOPLANATIC ANGLE BASED UPON D.L. FRIEDS
C----- DEFINITION
C
      COMMON /AIMO/ EATMC
      REAL ISOANG
      TPI=4.*ASIN(1.)
      CK=TPI/W
      CKSQ=CK*CK
      DELH=(HATMO-HT)/N
      HEIGHT=HG+DELH/2.
      DHT=DELH/2.
      SUM=0.
      DO 10 I=1,N
      CALL CN2E(HEIGHT,CN2)
      SUM=SUM+CN2*DHT**1.6666667
      HEIGHT=HEIGHT+DELH
      DHT=DHT+DELH
10  CONTINUE
      CN1=SUM*DELH
      DEN=2.91*CKSQ*CN1
      ISOANG=(6.68/DEN)**.6*.314
      RETURN
      END

```

```

SUBROUTINE ISCFIA (J,XNU,R,SECCMG,WAVE,XINT,HT,HG,TISO,N4,II)
C
C-----THIS SUBROUTINE COMPUTES THE ISOPLANATIC MTF FOR A FULL AO
C-----COMPENSATED SYSTEM DEVELOPED BY DL PRIEL
C
  DIMENSION H(23),C(19),C2(19),C4(19)
  DIMENSION TISC(N4)
  DIMENSION S(19),XNU(20),CN2(23)
  COMMON /ATMO/ HATMO
  IF (JJ.GE.1) GC IC 3C
  NE=20
  N=18
  DEIH=(HATMO-HT)/NE
  HEIGHT=HG+DEIH/2.
  DC 10 K=1,NH
  CALL CN2E (HEIGHT,CNSQ)
  CN2(K)=CNSQ
  H(K)=HEIGHT
  10 HEIGHT=HEIGHT+DEIH
  PI=3.1415926
  A13=1./3.
  A56=5./6.
  A572=5./72.
  A143=14./3.
  A9127=91./27.
  A73=7./3.
  A53=5./3.
  A12=1./2.
  DEBI=PI/2./N
  PHI=DEBI/2.
  DC 20 J=1,N
  C(J)=CCS (PHI)
  PHI=PHI+DEBI
  20 C2(J)=C(J)*C(J)
  30 C4(J)=C2(J)*C2(J)
  CONTINUE
  JJ=JJ+1
  XA=XNU*SECCMG/F
  DO 40 J=1,N
  S(J)=0.
  DC 110 K=1,NH
  X=H(K)*XA
  XX=CN2(K)
  IF (X.LT.0.1) GO TO 60
  IF (X.GT.10.) GO IC 80
  X2=X*X
  DO 50 J=1,N
  F=1.+X**A53-A12*(1.+2.*X*C(J)+X2)**A56-A12*(1.-2.*X*C(J)+X2)**A56
  50 S(J)=S(J)+F*XX
  GO TO 100
  X53=X**A53
  X2=X*X
  X4=X2*X2
  DC 70 J=1,N
  F=X53-A56*X2*(1.-A13*C2(J))+A572*X4*(1.-A143*C2(J)+A9127*C4(J))
  70 S(J)=S(J)+F*XX
  GO TO 100
  X13=X*(-A13)
  X73=X13/(X*X)
  DC 90 J=1,N
  F=1.-A56*X13*(1.-A13*C2(J))+A572*X73*(1.-A143*C2(J)+A9127*C4(J))
  90 S(J)=S(J)+F*XX
  100 CONTINUE
  110 CONTINUE
  XNU(1)=1./XA
  DO 120 J=1,N
  120 XNU(J+1)=114.88*DEIH*S(J)
  C
  C NOW INTEGRATE OVER PHI
  C
  CST=R**A53*SECCMG/WAVE**2
  SUM=0.
  DC 130 I=1,N
  130 SUM=SUM+EXP(-XNU(I+1)*CST)
  C
  C

```

C

```
XINT=SUM*DPHI*2./PI  
TISO(II)=XINT  
RETURN  
END
```

```

SUBROUTINE FNDREC (EXD,RHO,DIA,RHOU,DX,N4,IRRMTF)
C
C---- THIS SUBROUTINE DETERMINES WHAT VALUE OF RHO WOULD PRODUCE THE AC
C---- CORRECTED STREHL AS IF THERE WERE NO COMPENSATION AT ALL
C
REAL IRRMTF(N4)
C
R=RHOU
DR=RHOU/2.
NSIGN=-1
NSIGN=-1
10  CCNTINUE
CALL TRESEL (IRRMTF,LIA,N4,DX,SR,R)
IF (ABS(SF-EXD)/EXD.LT..1) GC TO 40
DIF=SR-EXI
IF (DIF.LT.0.) GC TO 20
NSIGN=1
GC TO 30
20  NSIGN=-1
30  CCNTINUE
IF (DIF.GE.0.) DR=DR/2
NSIGN=NSIGN
R=R-DR*NSIGN
GC TO 10
40  CCNTINUE
RHO=R
RETURN
END

```

```

SUBROUTINE TREREL (IRMTF,DIA,N4,DX,TREL,RHO)
C
C---- THIS SUBROUTINE COMPUTES THE RELATIVE INTENSITY DUE TO A TOTAL
C----- TILT CORRECTED SYSTEM FOR TURBULENCE ONLY.
C
      REAL IRMTF(N4)
      PI=2.*AR SIN(1.)
      SUM=0.
      DX2=DX/2.
      X=DX2
      DO 10 I=1,N4
      F1=IRMTF(I)
      CALL MTFATM(X,DIA,RHO,0.,F2)
      SUM=SUM+F1*F2
      X=X+DX
      CONTINUE
      TREL=SUM*2.*PI*DX
      RETURN
      END
10

```

```

SUBROUTINE TLIISC (D,OMX,OMY,RESTLT,SECCMG,HTRANS,HABVGD)
C-----THIS SUBROUTINE COMPUTES THE RESIDUAL TILT DUE TO ISOPLANATISM
C
COMMON /ATMO/ BATOMO
N=100
E56=5./6.
E53=5./3.
DS=(BATOMO-HTRANS)/N
H=BABVGD+DS/2
SUM=0.
C
DO 10 I=1,N
C
CALL CN2E (H,CN2)
C
Z=SECCMG*H
C
ARG1=({(D+Z*OMX)**2+(Z*OMY)**2})**E56
ARG2=({(D-Z*OMX)**2+(Z*OMY)**2})**E56
ARG3=(Z**2*(OMX**2+OMY**2))**E56
ARG4=D**E53
ARG5=({(Z*CMX)**2+(D-Z*OMY)**2})**E56
ARG6=({(Z*CMX)**2+(D+Z*OMY)**2})**E56
C
SUM=SUM+(4.*ARG4+4.*ARG3-ARG2-ARG5-ARG1-ARG6)*CN2
H=H+DS
10 CONTINUE
C----- THIS IS THE RESULTANT 2-SIGMA-P TILT DUE TO ISOPLANATISM.
C
RESTLT=SUM*DS*SECCMG*2.91/D**2*2.
C
RETURN
END

```



SUBROUTINE RELTCT (T,TR,TM)

C  
C----- WE HAVE FOUND THE DETAILED MTF CODE TO GIVE RESULTS  
C----- WHICH LIE BETWEEN AN ESS MODEL FOR FLOCCING AND A  
C----- MULTIPLICATIVE APPROACH. THIS SUBROUTINE IS AN ATTEMPT  
C----- AT BETTER MATCHING THE RESULTS OF THE MTF CODE BY  
C----- AVERAGING THE ESS AND THE MULTIPLICATIVE RESULTS.  
C  
C

T=(TR+TM)/2.  
RETURN  
END

```

SUBROUTINE BLCCM (D,E,S,T)
C
C----THESE BLOCKING IREL MODELS ARE CURVE FITTED TO GUTSMTF
C----BUNS FOR SIGS2'S GREATER THAN ABOUT 1.2. THE APERTURE
C----DISTRIBUTIONS USED HAD OBSCURATIONS OF .1 X THE OUTER
C----DIAMETER. IF FETTER IS REQUIRED, RECOMMEND BASELINING
C----TO THE GUTSMTF CODE AGAIN.

SQRTS=SQRT(S)
TEG=-.08705+SQRTS*2.91485+.1723*S
TEG=1./TEG
TRU=1.2877-SQRTS*2.6491+4.09603*S
TRU=1./TRU
T=(1.-(D/E)**2)*TED+(D/B)**2*TEG
IF (D.GT.E) T=TRG
RETURN
END

```

```

      SUPEROUTINE SCINT (SIGXZ,N,HTRANS,HGRND,WAVE)
C----- THIS ROUTINE COMPUTES THE VARIANCE OF THE LOG AMPLITUDE
C----- FOR A ZENITH ANGLE. THE RESULTS WILL ONLY BE USED
C----- IN THE EVENT THAT FULL AO IS UTILIZED IN THE RUN.
C
      COMMON /ATMO/ EATMC
      CK=6.28/WAVE
      HTOTAL=HATMO-HIFAKS
      DH=HTOTAL/N
      H=HTRANS*DH/2.
      C56=5./6.
      SUM=0.
      DO 10 I=1,N
      H56=H**C56
      CALL CN2E (H,CN2)
      SUM=SUM+CN2*H56
      H=H+DH
10    CONTINUE
      CK76=CK**(7./6.)*DH*0.56
      SIGXZ=SUM*CK76
      RETURN
      END

```

```

SUBROUTINE SINTIS (TAMP,SIGXZ,SECOMG)
C----- COMPUTE THE LOG AMPLITUDE SCINTILLATION VARIANCE
C----- FOR OFF-ZENITH CONDITIONS AND THE RELATIVE IRRADIANCE
C----- REDUCTION WHEN FOIL AO IS USED.
C
TAMP=EXP (-SIGXZ*SECCMG** (11./6.))
RETURN
END

```

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